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THESIS

PARAMETRIC PREDICTION OF THE TRANSVERSE DYNAMIC STABILITY OF SHIPS

by

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September, 1997

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PARAMETRIC PREDICTION OF THE TRANSVERSE DYNAMIC STABILITY OF SHIPS

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ABSTRACT

There currently exists no direct method for predicting the righting energy of a ship based on key geometric hull properties. Consequently, naval architects traditionally select hull parameters based on other constraints and merely check the dynamic stability indicators after designing the preliminary body plan. Quantifying these relationships would allow such indicators to be used as design variables in optimizing a hull form. Additionally, the hull form has a considerable impact on ship motion theory and dynamic stability criteria. This thesis suggests possible functional relationships, to predict the residuary stability of a design using basic hull parameters.

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Words can not express how grateful I am to my wife, Annette, for her continual support, strength and inspiration. Having her by my side has made me realize that it is not until we find something worth dying for that we truly start living.

Finally, this thesis is dedicated to all those who have lost their lives at sea. It is in their memory that we strive to understand the unpredictable ocean waters and improve the safety and seakeeping of our ships, in hopes that someday the phrase *Scientae Cedit Mare* may take on new meaning.

I. INTRODUCTION AND BACKGROUND

A. MOTIVATION AND SCOPE

During the preliminary phases of ship design, the designer is forced to select hull form parameters and coefficients with very little insight regarding key dynamic stability attributes the ship will ultimately have. Typically, designers will instead select parameters based on speed and powering requirements, while keeping in mind some general effects that parameters have on stability. One example of such an effect is that ships with a large beam will ordinarily have a high metacentric height, GM. Currently, it is not until the designer completes the first iteration of the design spiral and has a preliminary body plan, that some of the static stability characteristics, namely the righting arms, can be calculated. As a result, stability assessment has chiefly been a secondary check performed to the already designed ship, rather than being an actual design variable. Predictions of these stability characteristics, using parameters which the designer can easily quantify, would therefore, greatly aid in the optimization of the ship hull design.

Aside from the preliminary design perspective, there is also an obvious need to understand the motions of a ship in its environment. Static stability data alone is insufficient to thoroughly define how a ship will respond in heavy seas. The dynamics of a ship in a seaway result from a complex interaction of non-linear external forces with non-linear restoring forces. There has been much research in the areas of linear ship motion theory, in particular statistical dynamic stability (Rahola, 1939) and model testing (Amy, et. al., 1976), all striving to relate the dynamic response of the ship to a quantifiable stability criteria. Recent research has compared the motions of a ship to the dynamics of a non-linear oscillator, in which the righting arm curve is equivalent to the non-linear spring (restoring) force. (Falzarano, 1990) Since the shape and magnitude of this curve varies dependent upon loading and hull shape, it is critical that we understand these influences in order to precisely describe the ship motion. In fact, the roll restoring moment curve, or righting arm curve, is the single most influential element in determining the stability of the ship.

The scope of this research is aimed at determining functional relationships between the righting energy of a ship and its basic geometric characteristics, such as beam, length, depth, etc. A method introduced by Professor C. W. Prohaska in the late 1940's, which decomposes the righting arm curve into a weight component and a hull form component called residuary stability (Prohaska, 1947), was particularly suited for this analysis. This decomposition, as well as the properties of residuary stability, is discussed in detail in subsequent chapters. An analysis was conducted regarding the correlation of a non-dimensional residuary stability coefficient (C_{RS}) to other form parameters for a systematic series of ship hulls.

B. OVERVIEW OF ADVANCES IN RESIDUARY STABILITY

Prohaska's method provided the groundwork for establishing some approximate expressions relating certain hull form parameters to the righting arm at 30 degrees heel angle (Brown, 1979). Brown plotted the C_{RS} curves for numerous hull forms and performed a multiple linear regression analysis to establish the relationships. The drawback to Brown's formulae is that it only relates the form parameters to the righting arm at one specific angle of inclination. There has been little or no published work in which similar expressions are deduced for the righting arm over a range of angles.

Some have suggested that Prohaska's representation of the righting arm could be used to determine critical values of metacentric height (GM) or the vertical center of gravity (KG) based on known intact stability criteria (Krishna Rao, 1979). Krishna Rao adapted the intact stability criteria recommended by the Inter-Governmental Maritime Consultative Organization (IMCO) to a series of parametric equations based on representing the righting arms by means of residuary stability coefficients. Using values of C_{RS} at 15, 30, 35 and 40 degrees of inclination and equating the area under the righting arm curve through 30 degrees to be the requisite 0.055 meter-radians or 10.34 foot-degrees (IMCO, 1964), he established an empirical formula for each of the six intact stability criteria. The largest of the six GM values was selected as the critical GM, satisfying all six stability standards. This critical GM was converted to a critical KG value, by use of some historically proven formulae. After normalizing the critical KG with the

depth of hull (D), Krishna Rao found that the KG/D ratio remained almost constant for all of the ship variants that he tested, except for the ships with very narrow beams.

Another similar study describes the computation of the critical KG, satisfying the same IMCO criteria, using a numerical integration technique (Khoushy, 1979). Khoushy noted that the residuary stability remained constant for a given draft and that the integral of the residuary stability is a geometrical property of the draft and trim for a given ship, though this relationship was not determined.

C. THESIS OUTLINE

While a precursory look at some of the important advancements in the field has been presented, much of the analysis contained hereafter is heavily predicated on an understanding of the assessment of ship stability. Brief discussions relating to basic ship stability theory will follow in Chapter II, outlining the significance of static stability, comparing initial stability to stability at large angles of heel, and introducing the subject of dynamic stability. A synopsis of the important dynamic stability criteria will follow, which will illustrate the depth and detail at which stability requirements are measured, yet will also reveal some of the notable shortcomings of the criteria. The final discussion in the framework of this thesis pertains to the theory and development of residuary stability, which is the entire basis of the research conducted.

Chapter III contains the formulation of the analysis approach taken and discusses the tools and models used to aid in the investigation. A discussion of the results is contained in Chapter IV, along with the interpretation of the behavior of both the residuary stability and the residuary stability coefficient. These results are compared with the trends that Prohaska found to hold true. Also the behavior of $\overline{C_{RS}}45$, a parameter conceived during the course of this research, is presented in detail. Chapter V contains the methods in which functional relationships were derived in order to predict the righting energy of a ship using only basic geometric properties. It also includes an assessment of the accuracy of these parametric relationships. Finally, Chapter VI presents some of the potential applications for these relationships, ranging in scope from the field of ship design, to constraints on ship loading and operation, and to salvage operations.

II. STABILITY ASSESSMENT

Before discussing the parametric analysis, a clear understanding of the stability of ships is imperative. First, a brief discussion of static stability will be presented, addressing the primary indicators of static stability, hull form effects on stability and some approximate methods for stability assessment. A more direct concern of the naval architect however, is dynamic stability, since it is in dynamic conditions that ships are known to capsize. An overview of the various dynamic stability methods and criteria is presented, along with an analysis of the effectiveness of these methods. The chapter will end with an introduction to residuary stability, a method infrequently used by naval architects though extremely valuable to this research.

A. STATIC STABILITY

Static stability is the measure of a ship's ability, when initially at rest, to return to the upright condition after being disturbed by an upsetting force or moment. This implies that a quasi-static equilibrium is maintained during the heeling and righting process and that the motion has a single degree of freedom, that being rotation about the longitudinal axis. This, of course, is not the case for any ship underway in a seaway, however static stability is the foundation on which our understanding of ship dynamic stability is based.

1. Initial Static Stability

Initial stability is a subsection of static stability in that it is the ability of the ship to resist initial heel from the *upright* equilibrium position. The metacentric height (GM) is the primary measure of the initial stability of a ship. A vessel with a positive GM will tend to float upright and will initially resist external inclining forces, whereas a vessel with negative GM will cease to float upright when disturbed by even the most minute force (Gilmer and Johnson, 1975).

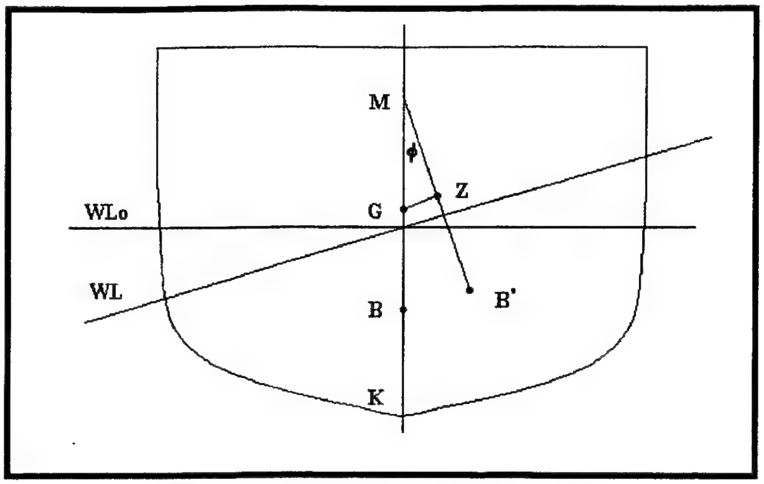

Figure 1. Stability at Small Angles

In addition to GM, the metacentric radius (BM), the vertical center of gravity (KG) and the vertical center of buoyancy (KB) are also significant features of static stability. In fact, GM is determined by the relationship

$$GM = KB + BM - KG \tag{1}$$

While GM and KB are strictly indicators of initial stability, KG and BM are important to overall stability as well. The center of buoyancy, or the point upon which the net buoyant force acts, is located at the centroid of the submerged hull. As a ship is heeled to an angle ϕ, as shown in Figure 1, the center of buoyancy shifts to the centroid of the new waterborne shape. KB is therefore only defined for the upright condition, since it is then that the center of buoyancy is directly above the keel. BM is purely a function of hull geometry and can be expressed as

$$BM_T = \frac{I_T}{\nabla} \tag{2}$$

where BM_T = transverse metacentric radius

I_T = moment of inertia of the waterplane area about the centerline

∇ = submerged volume of the hull.

As the ship is heeled, the shape of the waterplane area changes, thereby changing the moment of inertia. While KG is an important factor in the stability of a ship, it is solely dependent upon the ship's loading. Since this varies, it is common to determine the KB and BM based on hull shape and displacement and then to compute the KG required to produce a positive or minimum allowable GM.

2. Overall Static Stability

The righting moment is the result of a horizontal separation of the lines of action of the gravitational (weight) force and the hydrostatic buoyant force, due to the ship being heeled by an external force. The moment is quantified by the magnitude of the force, which is the displacement of the ship, multiplied by this separation which is referred to as the righting arm (GZ). Hence, the equation for the righting moment of a ship is

$$RM = GZ \times \Delta \tag{3}$$

Since ships at sea have a relatively constant displacement, it is therefore the righting arm that determines its righting moment. The righting arm is considered the predominant measure of the overall static stability of a ship to external forces.

Figure 2 shows a typical righting arm curve for angles of inclination from zero to 90 degrees. As a ship is inclined, the righting arm will increase as the center of buoyancy initially moves away from the centerline. At some angle of inclination, determined by hull shape, the center of buoyancy will begin to move back toward the vertical line of action of the gravitational force, and GZ decreases. One important feature of the righting arm curve is that the tangent to the curve at the origin represents the GM. This is closely associated, for angles less than about seven to ten degrees, with the relationship

$$GZ = GM \times \sin\phi \tag{4}$$

A similar expression, Equation (5), has been developed for ships said to be wall-sided. Although practically speaking, no ship is truly wall sided, many full-formed ships can be

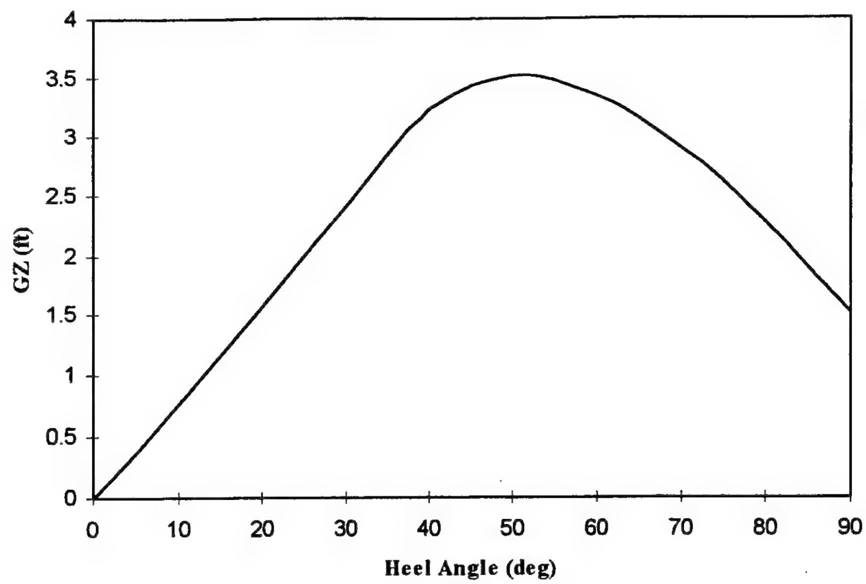

Figure 2. Righting Arm Curve

said to be wall-sided within the angles of inclination to be considered, perhaps up to about twenty degrees (Rawson and Tupper, 1983).

$$GZ = \sin\phi\left[GM + \frac{BM}{2}\tan^2\phi\right] \tag{5}$$

To truly comprehend the nature of ship stability however, an understanding of the righting levers and energies at larger heel angles is imperative. At angles greater than seven to ten degrees, there is no direct correlation between GZ and GM. In fact, at these angles, the metacenter itself is undefined because the lines of action of the buoyant force do not intersect the centerline at any one specific point. Instead, the "metacenter" moves up and away from the centerline as the angle of inclination is increased. At very large angles, it levels out and may even move down, depending on the particular hull geometry. This so called metacenter is termed the *pro-metacenter* and the path it forms is referred to as the *locus of pro-metacenters*. (Rawson and Tupper, 1983)

Our understanding of righting arms at large angles of heel is mostly qualitative. Although it is known that the shape of the righting arm curve is governed by the geometry

of the hull, it remains that the only way to construct the GZ curves is to integrate, numerically or manually, the immersed hull volume. During the preliminary phases of design, the naval architect must therefore rely on the general understanding of hull form influence on stability and, perhaps, use some approximation methods.

3. Hull Form Influence on Static Stability

Often an inflection point can be seen in the GZ curve to the left of the maximum righting arm. This inflection point roughly corresponds to the angle of deck edge immersion and will be used later in the analysis. Hull form will govern the angle at which this inflection occurs, as well as the angle of maximum righting arm and the angle of vanishing stability (GZ=0). The ship's center of gravity, along with hull form, determines the overall magnitude of the righting arms.

Of the principal dimensions of a ship, beam has the greatest influence on its transverse stability. An increase in the beam of a ship design will significantly increase the metacentric radius (since $I_T \propto B^3$), and hence GM. In general, increased beam will improve the stability at small angles and increase the value of the maximum righting arm, but will reduce both stability at large angles and the range of positive stability.

Assuming a constant center of gravity, changes in depth do not affect the righting arm until the angle of deck edge immersion. An increase in depth will tend to shift the maximum righting arm to the right and widen the range of positive stability. The danger the designer faces here though, is that increased depth will ordinarily move the center of gravity upward due to the addition of high structural weight.

Ships with flaring sides develop large righting arms due to the rapid increase in waterplane area and large shift of the center of buoyancy as the ship is inclined. Tumblehome or extreme deadrise in the vicinity of the waterline will have the opposite effect and tend to have very shallow GZ curves. Figure 3 illustrates this through a comparison of a simple rectangular barge with two other shaped barges. The second and third barges are identical to the first beneath the waterline, but have equal amounts of flare and tumblehome respectively.

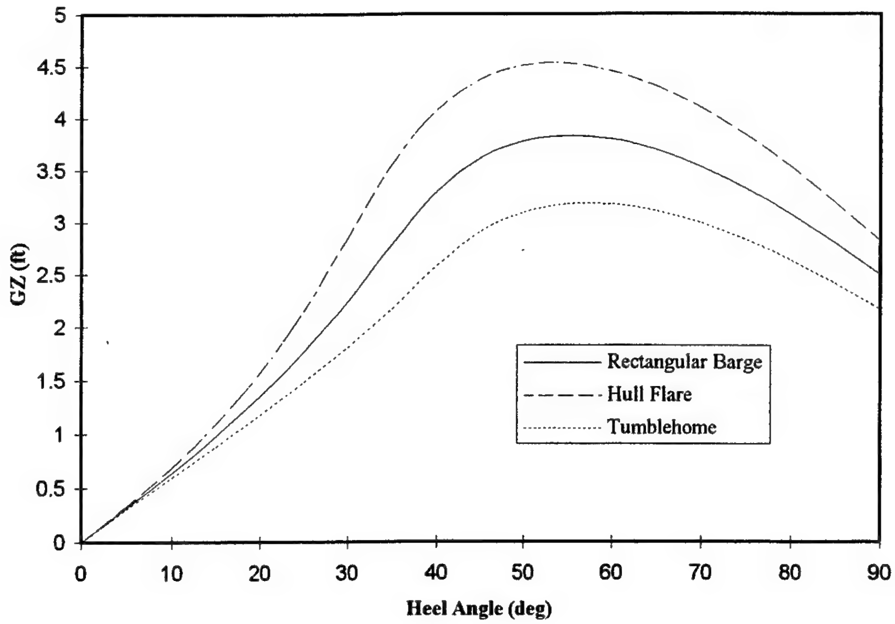

Figure 3. Righting Arm Comparison of Flare vs.Tumblehome

4. Approximate Methods

There are numerous methods that have gained wide acceptance for approximating the value of certain initial stability parameters. Perhaps the best known is the Morrish Formula which estimates the distance of the center of buoyancy from the waterline and is remarkably accurate for conventional ship forms (Rawson and Tupper, 1983). A modified version of the formula, Equation (6) below, estimates the vertical center of buoyancy and is more convenient for today's naval architect. Another approximation of KB is given by Posdunine's Formula, Equation (7), which also provides values close to those calculated for merchant vessels of ordinary form. In practice, KB is expected to be roughly 0.52T for full-form ships and 0.58T for fine-lined ships, and will approach 0.5T as the hull form approaches a rectangular prism (Bartholomew, Marsh and Hooper, 1992).

$$KB = \frac{1}{3}\left(\frac{5T}{2} - \frac{\nabla}{A_{WP}}\right) \tag{6}$$

$$KB = T_m \frac{A_{WP}}{A_{WP} + \frac{\nabla}{T_m}} \tag{7}$$

A relationship to estimate the transverse metacentric radius was developed by Saunders and Mills. Equation is a form of their general equation, modified for a frigate type vessel.

$$BM_T = \frac{LB^3}{12\nabla}\left[1.204\,C_P - 0.157\right] \tag{8}$$

B. STABILITY CRITERIA

Stability criteria are intended to ensure that vessels have sufficient righting energy to resist overturning by disturbing forces that can reasonably be expected during normal service. Through the years, we have advanced our understanding of ship motion and the probability of capsizing to enable us to establish conservative design and loading criteria to avert most casualties. Today, there are numerous criteria developed by classification societies and government regulatory bodies, that are enforced during ship design, construction and loading.

The simplest form of stability standard is a minimum GM requirement or initial stability criteria. While it is a commonly used criterion, most regulatory bodies employ more stringent forms of dynamic stability criteria. Most of the dynamic stability standards can be classified as either probabilistic or energy-balance type. Other methods of stability standards are being developed, some of which rely on the dynamic motion of ships or a specified wave form and direction, however they have not yet gained widespread acceptance. (Bartholomew, Marsh and Hooper, 1992)

Most regulatory bodies have instituted a wind heeling or weather criterion to ensure sufficient righting energy to sustain an upsetting moment created by wind pressure on the ship's profile coupled with the viscous drag force on the underwater hull. The righting energy, at a given angle Φ, is defined as the work required to restore a ship to the upright condition after a heeling force has slowly inclined it to that angle. It is proportional, by a factor of displacement, to the area under the GZ curve and is expressed analytically as

$$\textit{Righting Energy} = \int_0^{\Phi} \Delta\, GZ_{\phi}\; d\phi \tag{9}$$

In most cases, the upsetting moment is superimposed as a *heeling arm* on the GZ curve as shown in Figure 4. For the U. S. Navy's Damage Stability Criteria, one of the conditions is that Area 1 in the diagram must be 40 percent larger than Area 2.

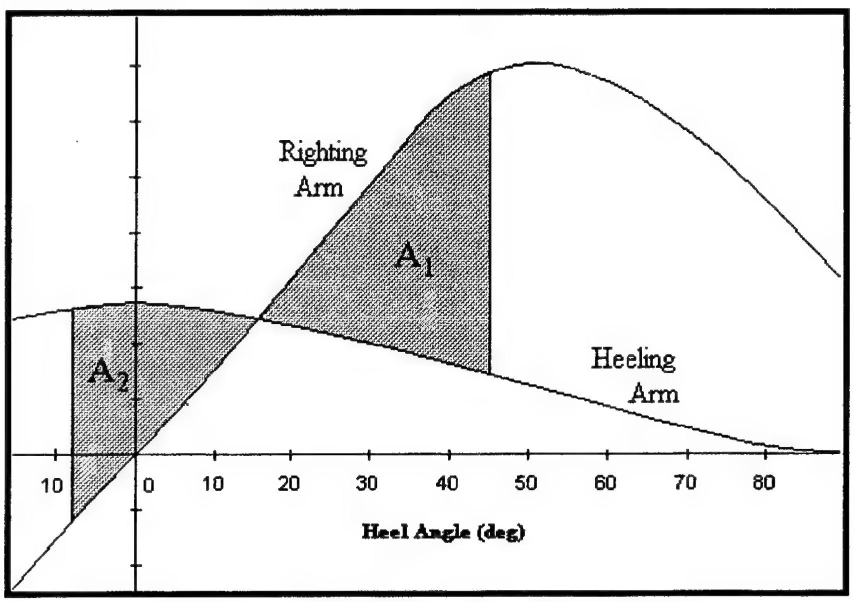

Figure 4. USN Damage Stability Criteria

Other criteria compare the righting energy of the ship to the energy of an external force such as wind, lifting heavy weights, high speed turns, towing effects or the static effect of topside icing or water on deck. (Sarchin and Goldberg, 1962) A detailed account of the current dynamic stability standards is presented by Bartholomew, et. al., (1992).

Although they are basically conservative, current stability standards are not perfect. There are many documented cases of ships, which met the applicable stability criterion, that were lost at sea due to capsizing or sinking. The British fishing trawler *Gaul* was a new, well-equipped ship when it was lost when it capsized in heavy weather in the mid-1970's. Another instance was the capsizing and loss of the Danish bulk carrier *Edith Terkol*, which at the time of the accident, met all the intact stability requirements of IMCO. (Amy, et. al., 1976) Clearly, a better understanding of ship dynamics is needed, in order to improve the safety standards of our ships.

C. RESIDUARY STABILITY THEORY

Prohaska (1947) introduced the concept of residuary stability whereby the righting arm could be expressed as the sum of two independent terms, one loading dominated and one hull form dominated. He suggested that

$$GZ = GM \sin \phi + MS \tag{10}$$

where MS represents the residuary stability of the hull form. It can be seen in Figure 5, which shows the stability of a ship at large angles of heel, that the movement of the pro-metacenter is the source of this additional term.

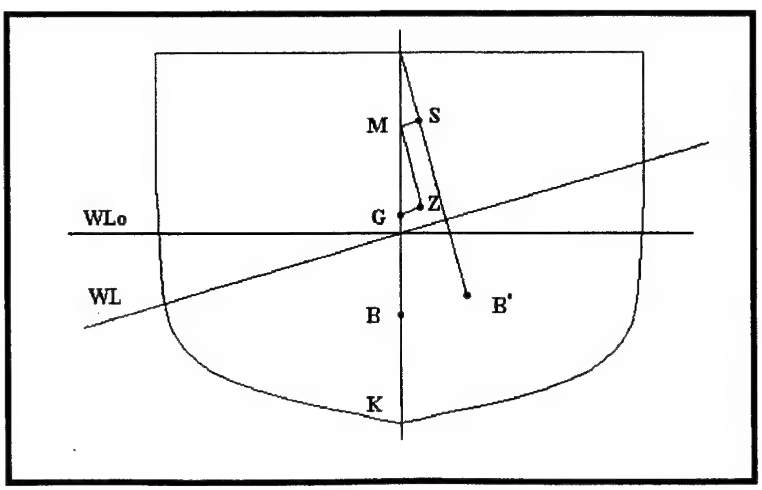

Figure 5. Stability at Large Angles

To facilitate non-dimensional plotting, he also introduced the residuary stability coefficient, C_{RS}, whereby

$$C_{RS} = \frac{MS}{BM_T} \tag{11}$$

Figure 6 shows curves of C_{RS} for various sized tankers and warships, calculated using General HydroStatics (GHS) software, for angles of heel up to 90 degrees. It can be readily seen that the positive C_{RS} at lower angles is what causes the GZ curve to have a steeper slope than the sine curve used in Equation (4). At higher angles, C_{RS} quickly becomes negative, drawing the GZ curve down toward the unstable region. The transition point between the lower and higher angles, although not easily discerned, corresponds to the point where the deck edge is immersed. In general, GZ can be thought of as getting its height from GM and its shape from C_{RS}.

Residuary stability however, is not merely hull form "dominant;" it is entirely independent of the location of the center of gravity. This is illustrated in Figure 7, which shows the CRS curves for a fine-lined hull with varying heights of center of gravity (KG). While this is true, it can not be said that residuary stability is independent of loading all together. The extent of loading or total weight will determine the displacement, and hence the draft, of the vessel which greatly influences the residuary stability.

Prohaska's further research into residuary stability and the effects of hull form on transverse stability resulted in the broad conclusion that the ratios of beam to draft (B/T) and depth of hull (B/D) have a comparatively greater influence on transverse stability than do the coefficients of form (i.e. fullness parameters). His work included the analysis of C_{RS} for a series of 42 systematically varied hull forms, covering the range of fullness coefficients seen in the merchant ship fleet of the day. (Prohaska, 1951)

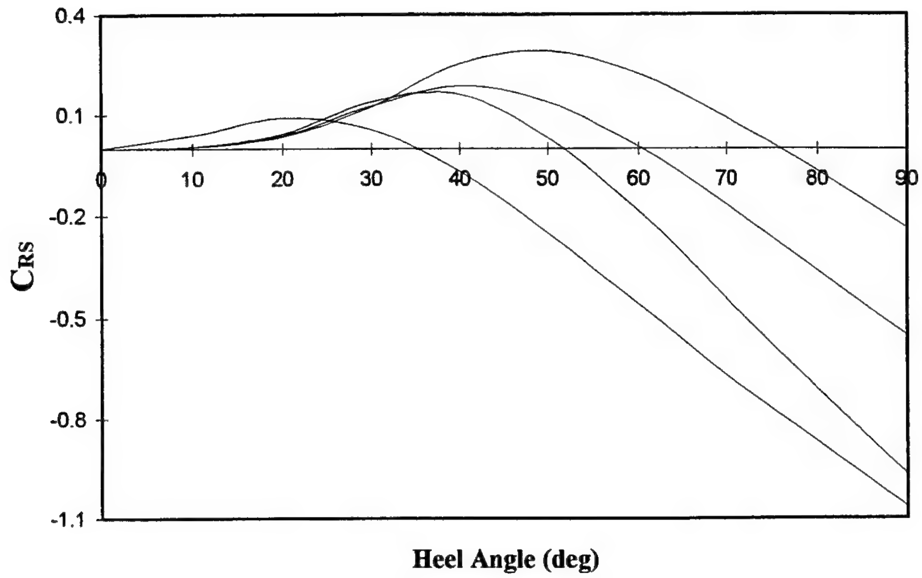

Figure 6. Residuary Stability Coefficient Curves

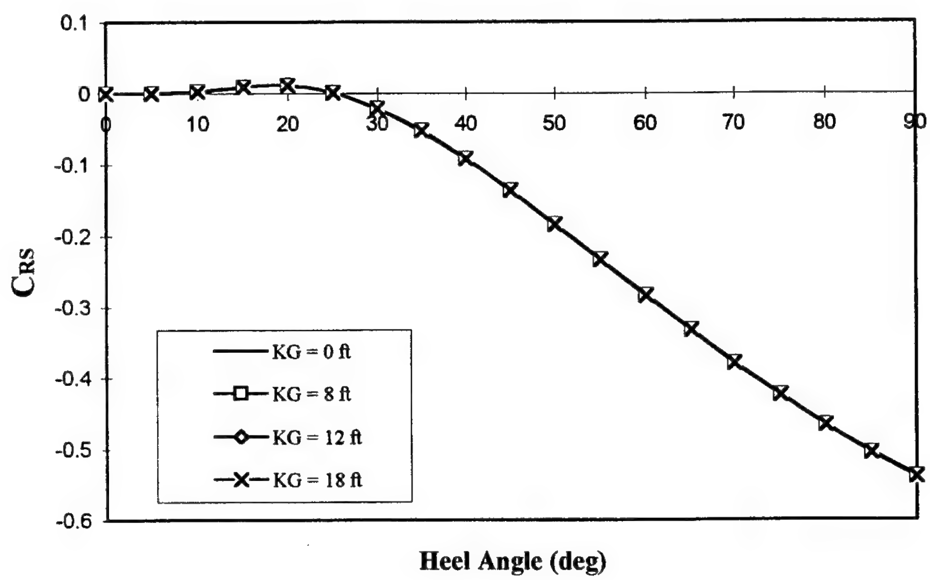

Figure 7. Residuary Stablitity Coefficient for Various KG

Among the specific conclusions from his study were:

- For constant B/D, the highest C_{RS} value occurs at a draft of one-half of the depth
- For constant C_{WP}, C_{RS} decreases with C_B
- For constant C_M, increased deadrise increases C_{RS} for high drafts but decreases C_{RS} for low drafts

This provided the groundwork for others who established approximate expressions relating some form parameters to the residuary stability at 30 degrees (Brown, 1979). Specifically, Brown plotted the C_{RS} curves for numerous hull forms and performed a multiple linear regression analysis to establish the following relationships:

$$C_{RS}(30) = 0.8566 - 1.2262\frac{KB}{T} - 0.035\frac{B}{T} \qquad (12)$$

$$C_{RS}(30) = -0.1859 - 0.0315\frac{B}{T} + 0.3526\,C_M \qquad (13)$$

where $C_{RS}(30)$ = residuary stability coefficient value at 30 degrees

C_M = midship section coefficient

The drawback to these formulae is that they only relate the form parameters to the residuary stability at one specific angle of inclination. There has been little or no published work in which similar expressions are deduced for the righting arm over a range of stability.

Attempts have been made to use the residuary stability method, in conjunction with dynamic stability standards, to closely approximate the maximum KG allowed for a vessel. Six criteria, recommended by the Inter-Governmental Consultative Organization (IMCO, now simply IMO), were used to develop six parametric equations to find the critical values of GM. Using the approximation methods for initial stability parameters, the most conservative of these six values was converted into a critical KG. It was discovered that,

except for ships with a narrow beam, the ratio of the critical KG to the depth remained constant for all vessels tested. (Krishna Rao, 1979)

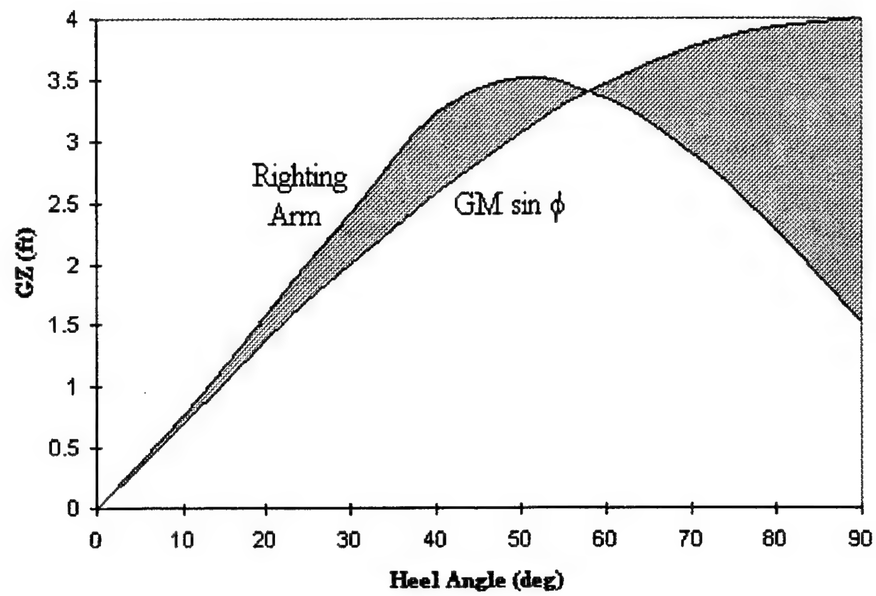

Figure 8. Residuary Stability Contribution

Integration of the C_{RS} curve is analogous to the righting energy of the hull form, since the area under the curve is proportional (by a factor of $BM_T \times \Delta$) to a section of the righting energy. Specifically, it is proportional to the righting energy minus the area under the GM sin ϕ curve, the shaded areas shown in Figure 8. This method was used in another study which involved computation of the critical KG, satisfying the same IMCO criteria. In the process, it was noted that the integral of the residuary stability is a geometrical property of the draft and trim for a given ship, which supports the findings of Prohaska and Brown. (Khoushy, 1979)

III. ANALYSIS APPROACH

As previously stated, the objective of this research was to establish functional relationships between the basic geometric characteristics of a ship and its righting energy, or more specifically its residuary stability coefficient. Prohaska's method was chosen for this analysis because it separates the hull form component of the righting arm from the weight component. In order to determine the functional relationships between hull form parameters and the residuary stability coefficient, it was first necessary to define a collection of hull forms which exhibits the full range of hull parameters. Intact stability calculations were then performed for each hull model at specific loading conditions. In order to analyze the resulting data, a select group of control parameter were determined, against which the C_{RS} curves could be compared.

A. SELECTION OF BASE SHIPS

A standard series of hulls, such as Series 60, was initially considered for this analysis since the systematic variations in hull shape are already created. This approach was precluded by several factors: 1) most standard series do not represent a full range of parameters, but are instead associated with a particular hull classification (i.e. cargo ship), 2) the lack of available computer-based series, and 3) the relative difficulty in digitizing ship body plans or entering offsets by hand. Since GHS uses a straight line interpolation between offsets, an external interpolation method would be needed to fair the hull.

An alternate approach was formulated using two hulls which have opposite extremes of hull fineness and displacement, a frigate hull and a tanker hull, to bound the typical range of hull parameters. The frigate hull chosen, the U. S. Navy's FFG-7, is a light displacement ship that has an extremely fine hull form ($C_B = 0.45$). Its hull shape includes flare at both the bow and stern and considerable deadrise. The U.S. Naval Ship T-AO 187, a fleet oiler with a classic tanker design, is a much higher displacement and fuller ship ($C_B = 0.64$) with virtually no flare or deadrise. The body plans of these two vessels are shown in Figure 9, and their principal characteristics are listed in Table I.

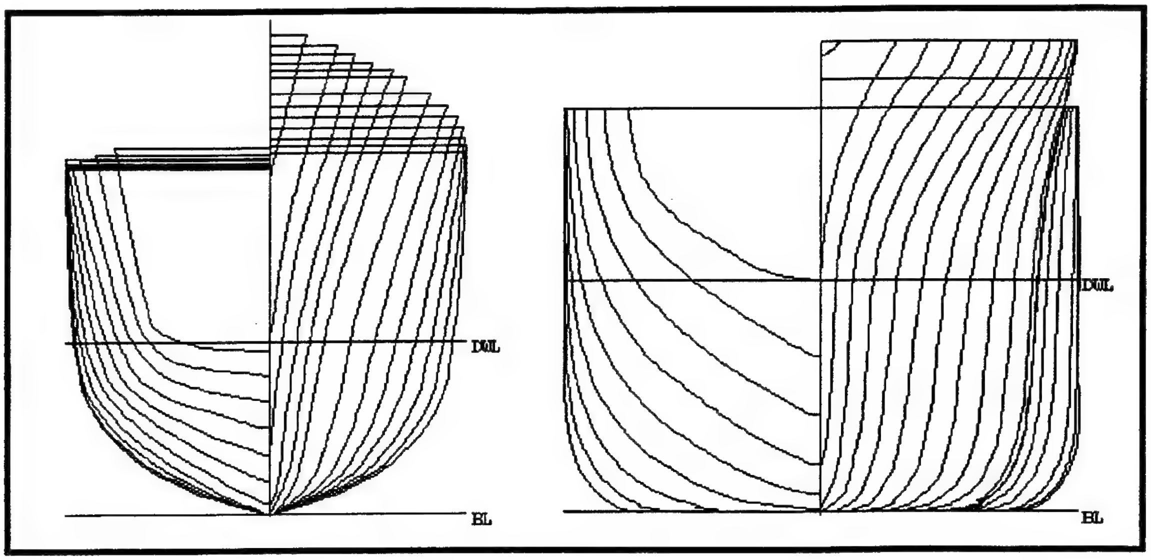

Figure 9. Body Plans of the FFG-7 Frigate Hull and the T-AO 187 Tanker Hull

	FFG-7	T-AO 187
Length, LBP (ft)	408	650
Beam (ft)	44.8	97.7
Depth (ft)	30	60.8
Design Displacement (l.tons)	4050	40,800
Prismatic Coefficient (C_P)	0.60	0.65
Midship Coefficient (Cx)	0.75	0.98
Block Coefficient (C_B)	0.45	0.64

Table I. Principal Characteristics of the FFG-7 Frigate and the T-AO 187 Tanker

The list of offsets for the FFG-7 frigate and T-AO 187 fleet oiler were exported from the Advance Surface Ship Evaluation Tool (ASSET) using a Ship Hull Characteristic Program (SHCP) file format. The hull forms were then modified, using General HydroStatics, by scaling the hull geometry in the vertical or transverse direction, or a combination of the two coordinates. Scaling a hull dimension in GHS is performed on a percentage basis of the existing dimension. Although the capability was available, the hull geometry was not scaled in the longitudinal direction, as a vessel's length has negligible impact on its transverse stability. By scaling the parent hull, rather than creating new hulls, the derivatives maintained virtually the same prismatic and block coefficients. This allows an

analysis to be conducted for a single variable change, instead of having to interpret whether the resulting behavior was caused by the variable change or the change in form coefficient. A list of the principal dimensions and form coefficients of all of the hull derivatives used in this research is shown in Appendix A.

B. COMPUTATION OF RIGHTING ARMS AND RESIDUARY STABILITY

The hydrostatic conditions and the righting arms (GZ) were computed using GHS. In constructing the righting arm curve, GHS performs the numerical integration necessary to compute volumes, centroids, and moments of inertia using the trapezoidal method. The trapezoidal method is used over the Simpson's rule, popular among naval architects, because of its flexibility when integrating odd shapes (i.e. deck-edge discontinuity) and because it never overestimates a concave-upward curve (Creative Systems, 1993). While any error is undesirable, the small error incurred using this method will lead to more conservative righting arms. Righting arm calculations were performed at five degree intervals, from the upright condition to 90 degrees of inclination, to improve the accuracy of the numerical integration.

In addition to the righting arm curves, GHS was used to compute the hydrostatic data, such as draft, GM_T, BM_T and KB, necessary for subsequent calculations. To obtain this, GHS required an input of the displacement (or draft could be input and displacement computed) and center of gravity of the model. The residuary stability (MS) curves were then calculated by rearranging Equation (10) and thus removing the loading dominant term from each of the GZ data points.

$$\mathbf{MS = GZ - GM \sin \phi} \tag{14}$$

The GM referred to here is the transverse GM in the upright condition. Each data point was then further normalized by the initial BM_T to obtain the C_{RS} curve.

For standardization, the center of gravity was always taken to be amidships on the centerline and vertically located at the baseline. Since KG is dependent upon loading and could take on any value, it is convenient to perform the hydrostatic calculations with KG

equal to zero. If necessary, righting arms can easily be adjusted for actual values of KG by use of a correction factor. Furthermore, the vertical center of gravity of a ship has absolutely no effect on its residuary stability.

C. SELECTION OF CONTROL PARAMETERS

In order to evaluate trends in the residuary stability of these hulls, it was first necessary to determine the parameters that would serve as the control variables for the numerical experiments. These control variables establish the basis on which the parent hulls were modified, but the overall analysis will not be constrained to consider only these variables for the stability predictions. Non-dimensional ratios were used whenever possible, to normalize the data and hopefully standardize the results for vessels of any size.

The parameters that seemed to be most significant from previous research were displacement ratio (D/d), beam to depth ratio (B/D), draft to depth ratio (T/D) and beam to draft ratio (B/T). Other parameters widely used in previous research, such as vertical center of gravity to depth ratio (KG/D) and vertical center of buoyancy to draft (KB/T), were discounted since they are dependent upon more than just basic geometric parameters. Conversely, one additional parameter would be considered, the beam to freeboard ratio (B/F), since it is well established that the hull form above the waterline is important to residuary stability.

Initially, ordinary rectangular barges were used to determine the fundamental effects of some of these parameters on residuary stability. Rectangular barges were used both for their simplicity of design and because they have clearly defined "corners" which either emerge from the water or get immersed in the water when the ship is inclined. The angles at which this happens, the angle of deck edge immersion (ϕ_D) and the angle of bilge pocket emergence (ϕ_B), shown in Figure 10, were suspected to have an influence on the residuary stability. Three sizes of rectangular barge were used: Barge 1: a barge with principal dimension the same as an FFG-7 frigate with a low draft (low T/D), Barge 2: a barge with the same beam as the first but with a very shallow depth, and Barge 3: a barge with a large depth and a deep draft (high T/D). The high and low T/D ratios were used to give separation between the two angles of interest. From each of these three barges a

family of variants were derived by scaling either the beam or depth (or both) in GHS. The variations in beam and depth were, with few exceptions, held within ten percent of the original dimension.

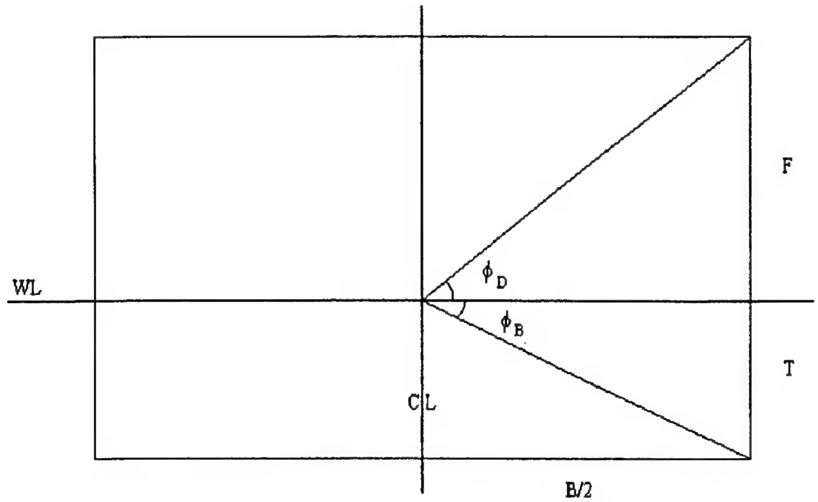

Figure 10. Angles of Deck Edge Immersion and Bilge Pocket Emergence of a Barge

It can be seen from Barge 1 that beam has an earlier effect on residuary stability than does depth. Since beam affects the transverse moment of inertia, its influence is apparent even at small angles of inclination, but it is not until higher angles that the deck edge is immersed. It is also evident that both decreasing beam and increasing depth have a positive influence on residuary stability. Figures 11 and 12 show the residuary stability curves of the derivatives of Barge 1. Since the depth is large, the residuary stability curve for all of the variants having changes in depth follow the parent barge until approximately 45 to 50 degrees. Beyond that point, the curves diverge; the variants with increased depth having greater residuary stability (or less negative in this case). Conversely, the variants with changes in beam show residuary stability curves that differ starting at a relatively low angle (approximately 15 to 20 degrees). The variants having decreased beam have the higher MS values, with wide separation at large angles of heel.

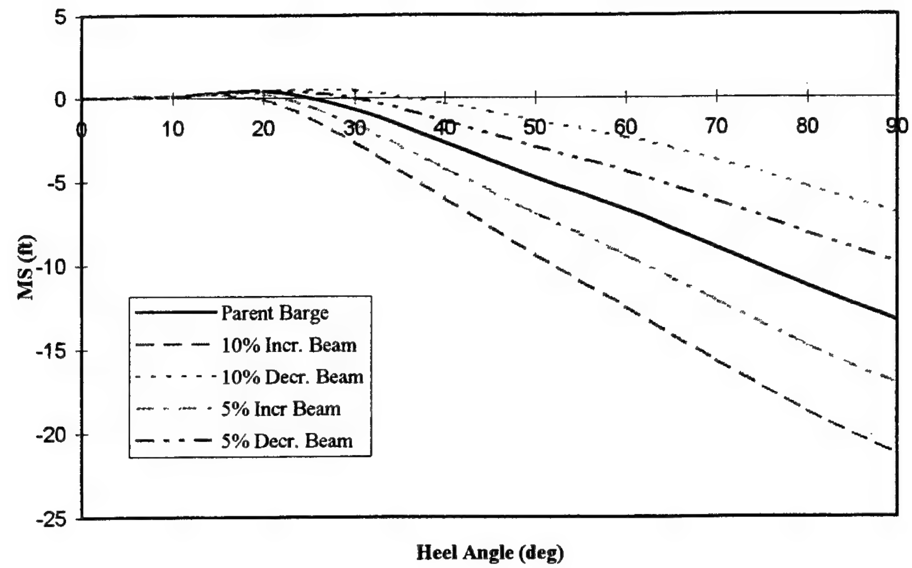

Figure 11. Residuary Stability for Changes in Beam (Barge 1)

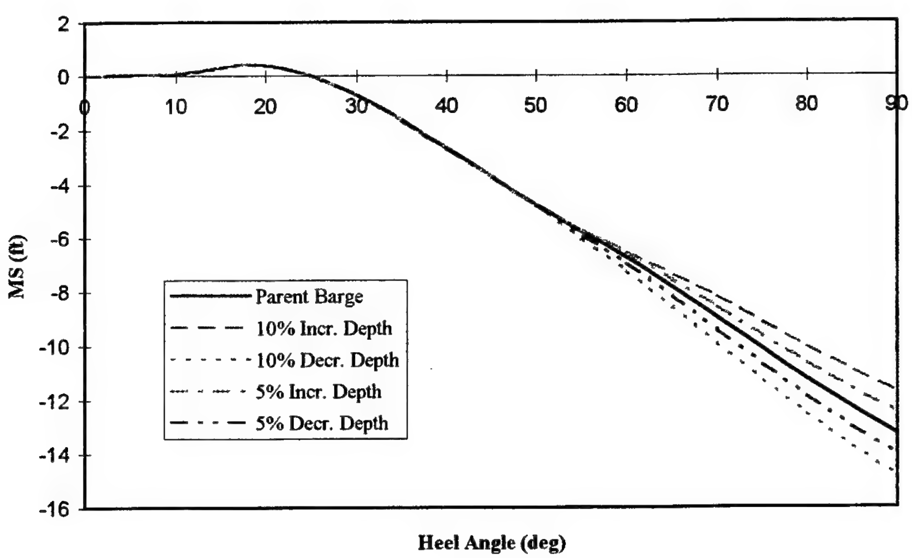

Figure 12. Residuary Stablity for Changes in Depth (Barge 1)

It was observed during these trials that the angles in which the two sets of curves began to diverge appeared to correspond to the angle of deck edge immersion and the angle of bilge pocket emergence respectively. Table II lists the variants along with their principal dimensions as well as these two angles. Although the bilge pocket emergence angle would not be expected to be as pronounced for a ship with fine lines and curving bilges, it was hypothesized based on this behavior that C_{RS} would relate in some way to these angles.

				Deck Edge	Bilge Pocket
	Beam	Depth	Draft	Immersion	Emergence
Parent	46.94	31	7.31	45.27	17.30
10% Beam Increase	51.63	31	6.65	43.33	14.44
10% Beam Decrease	42.25	31	8.12	47.29	21.03
5% Beam Increase	49.29	31	6.96	44.29	15.77
5% Beam Decrease	44.59	31	7.7	46.26	19.05
10% Depth Increase	46.94	34.1	7.31	48.78	17.30
10% Depth Decrease	46.94	27.9	7.31	41.26	17.30
5% Depth Increase	46.94	32.55	7.31	47.08	17.30
5% Depth Decrease	46.94	29.45	7.31	43.33	17.30

Table II. Geometric Characteristics of Barge 1 with Low T/D

This theory was reinforced by the curves of Barge 2 and 3. Barge 3, the shallow depth barge, was designed with no separation between the deck edge immersion angle and the bilge pocket emergence angle. That is to say that its draft was approximately one-half of its depth ($T/D \approx 0.5$). As seen in Figures 13 and 14, once the divergence occurs at this angle (approx. 10 to 20 degrees), the separation remains constant among the variants with depth changes. Once again, the variants with beam changes continue to diverge at large angles, as they did for Barge 1. The C_{RS} curve in Figure 15, however, does not exhibit this behavior since the residuary stability is now normalized by BM_T, which is the term that contains the moment of inertia changes. This curve shows that beyond the differences that occur at this critical angle, the C_{RS} curve among the variants is virtually identical. Barge 3, which had a low deck edge immersion angle and a high bilge pocket emergence

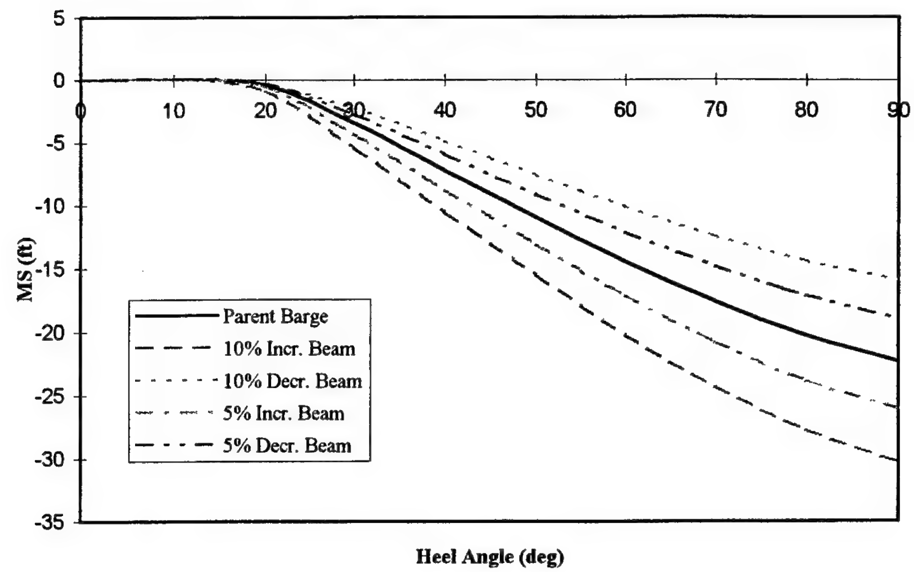

Figure 13. Residuary Stability for Changes in Beam (Barge 2)

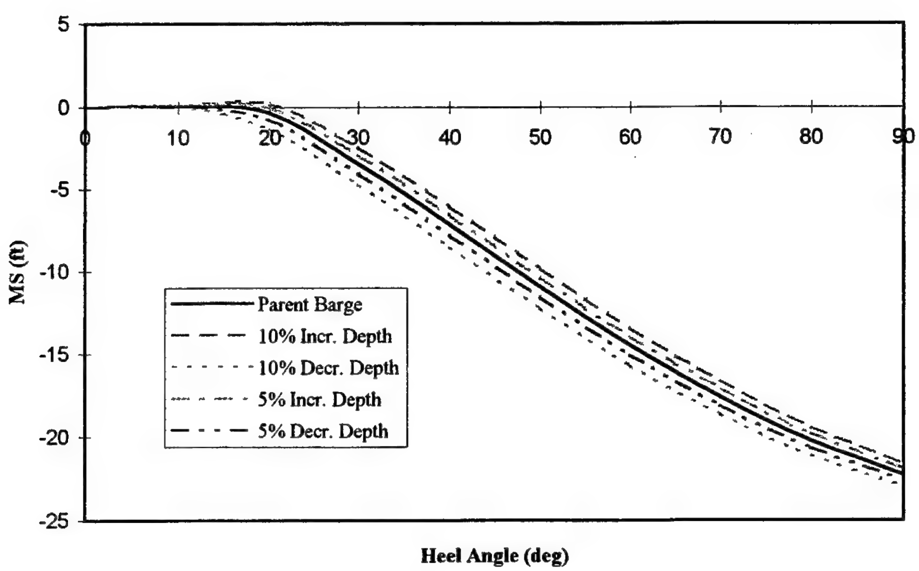

Figure 14. Residuary Stablity for Changes in Depth (Barge 2)

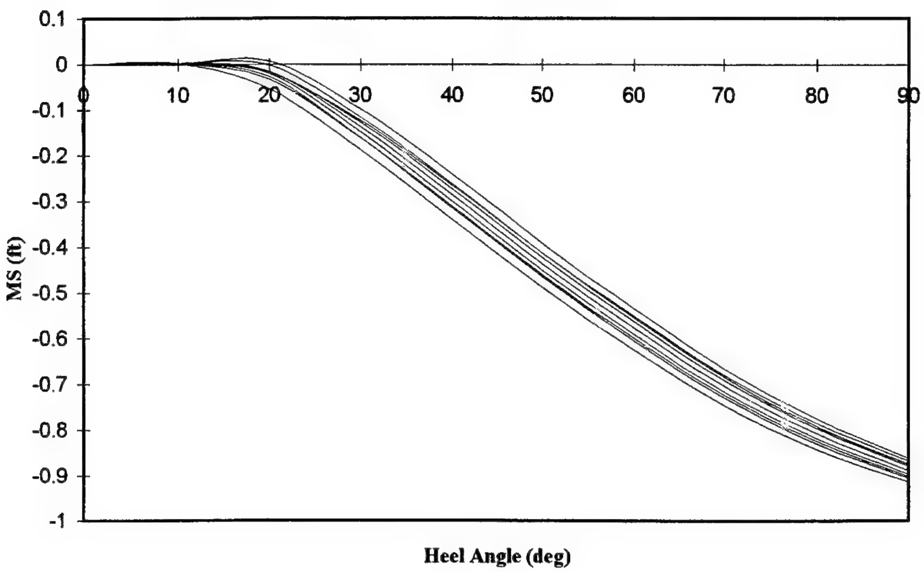

Figure 15. Residuary Stability Coefficient for Barge 2 and Variants

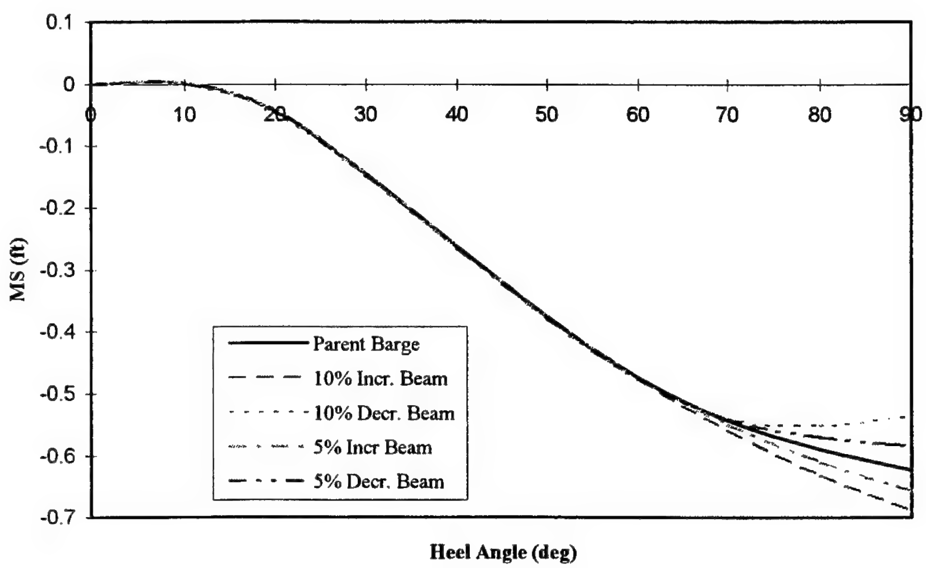

Figure 16. Residuary Stablity Coefficient for Barge 3 and Variants

angle, demonstrated this perfectly. As seen in Figure 16, the variants of this barge exhibited identical CRS values for angles less than 60 degrees, which is within ten degrees of the bilge pocket emergence of each.

The behavior of the MS and CRS curves of these three barges convincingly indicates that there is a relationship between one or both of these angles. These angles relate to basic geometric parameters as indicated in Equations (15) through (18).

$$B/F = 2 \cot(\phi_D) \tag{15}$$

$$B/T = 2 \cot(\phi_B) \tag{16}$$

$$B/D = \tfrac{1}{2} [\tan(\phi_D) + \tan(\phi_B)] \tag{17}$$

$$T/D = \tan(\phi_B) / [\tan(\phi_D) + \tan(\phi_B)] \tag{18}$$

It was therefore determined that B/F, B/T and B/D would be considered primary control variables for this analysis. Since the T/D ratio appears to influence the particular point, during inclination, that the curves separate, it was included in this group as well.

IV. RESULTS OF PARAMETRIC ANALYSIS

A. BEHAVIOR OF MS AND C_{RS}

The first phase of the research was to analyze the behavior of MS and C_{RS} for the hull forms chosen. Initially, just the single parameters of beam and depth were varied. To facilitate this, the FFG-7 and the T-AO were geometrically scaled, as described earlier. In subsequent trials however, combinations of beam and depth changes were made, while keeping one or more of the control variables constant. Since B/D did not require knowledge of the waterline, the models for that trial were simply scaled with the same factor in both the transverse and vertical directions. The models for the B/F and B/T trials were developed by adjusting beam first to determine the new draft and then adjusting depth. In most cases, the form change associated with scaling depth did not appreciably alter the draft. In some instances however, a second iteration was required to achieve the desired B/F or B/T ratios. Since multiple T/D ratios can be achieved for a single hull, it was not necessary to create specific models for the T/D studies.

In the first trial, beam was varied while maintaining constant displacement, which caused draft to vary. Depth was held constant for this trial. The results were similar to those found with the barges, in that the effect on residuary stability was nearly immediate for beam changes. Figures 17 and 18 show that the MS and C_{RS} curves for this trial diverged within ten degrees of inclination. Next, depth was varied in the same manner, maintaining constant displacement and constant beam. Unlike the barge however, the scaling of depth affected the entire hull form, since it was performed keeping the form coefficients constant. Although this would cause one to expect an early departure of the curves, they did not diverge until approximately 30 degrees (Figures 19 and 20).

As expected, the trends of decreasing beam and increasing depth both improving residuary stability were evident, however when these first two trials were compared, an interesting result became apparent. As shown in Figure 21, the MS curves of the two trials seemed to group together beyond 40 to 45 degrees. It appears, judging from this,

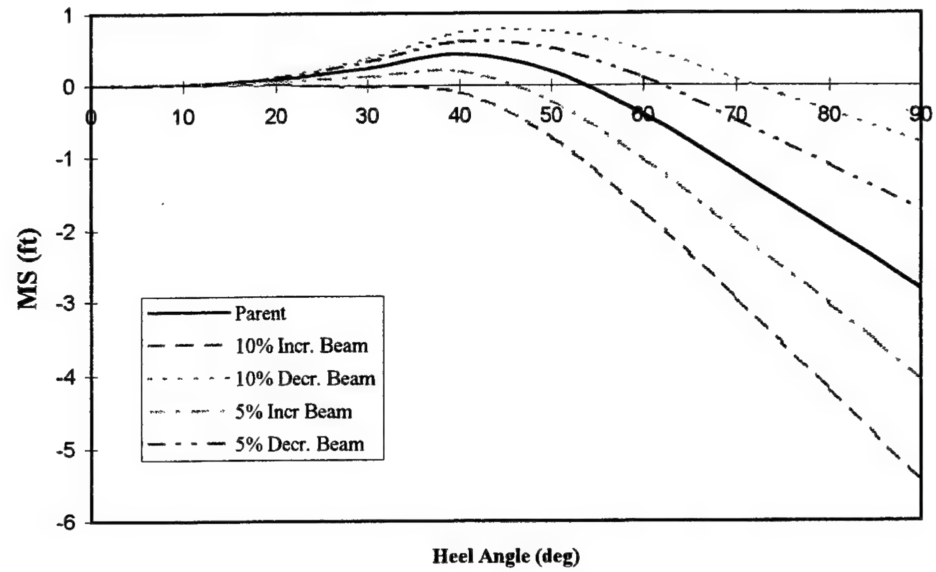

Figure 17. Beam Effects on Residuary Stability for FFG-7

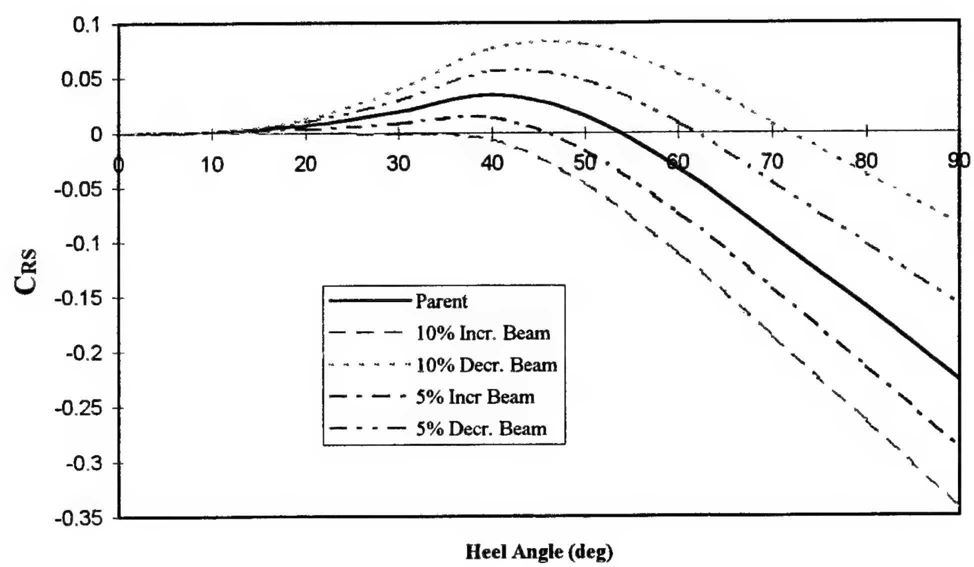

Figure 18. Beam Effects on Residuary Stability Coefficient for FFG-7

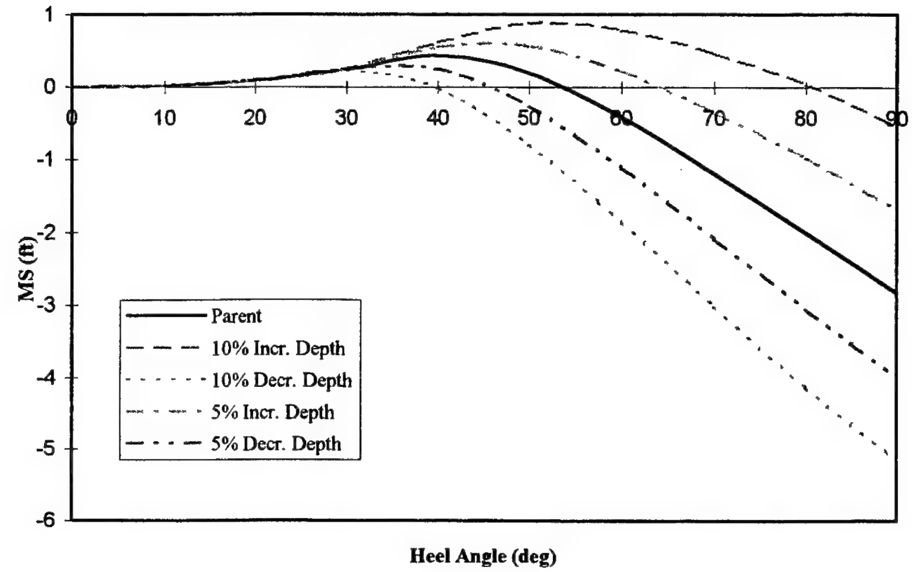

Figure 19. Depth Effects on Residuary Stability for FFG-7

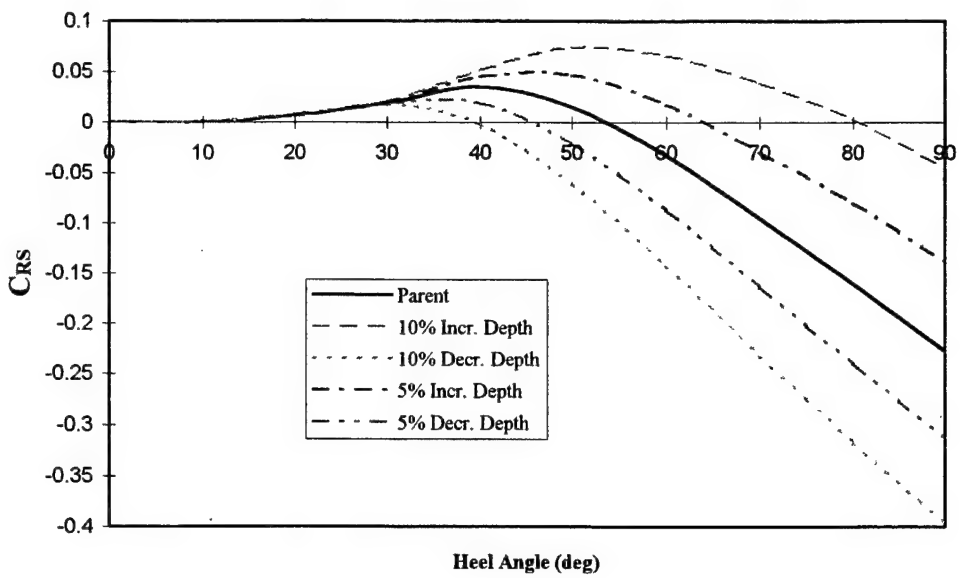

Figure 20. Depth Effects on Residuary Stability Coefficient for FFG-7

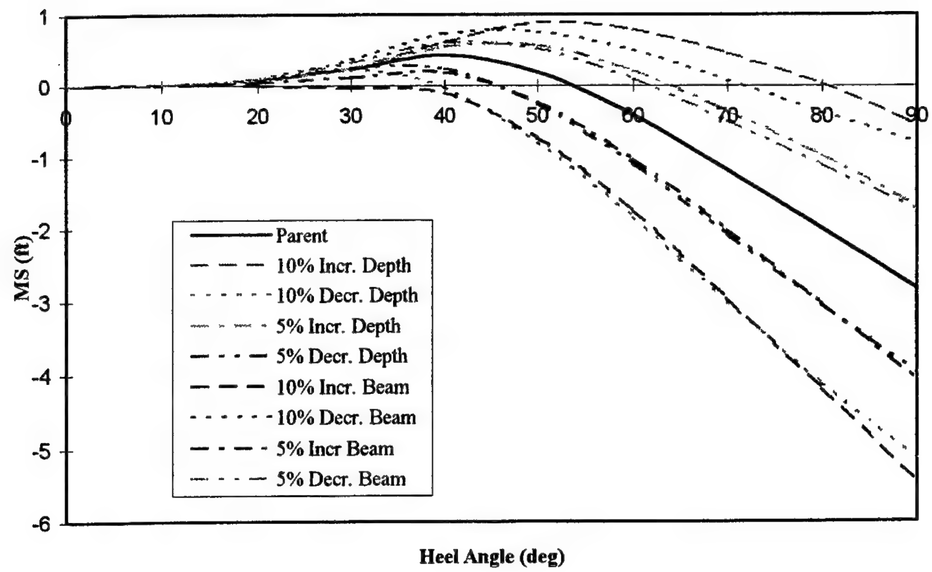

Figure 21. Comparison of Beam and Depth Effects on MS for FFG-7

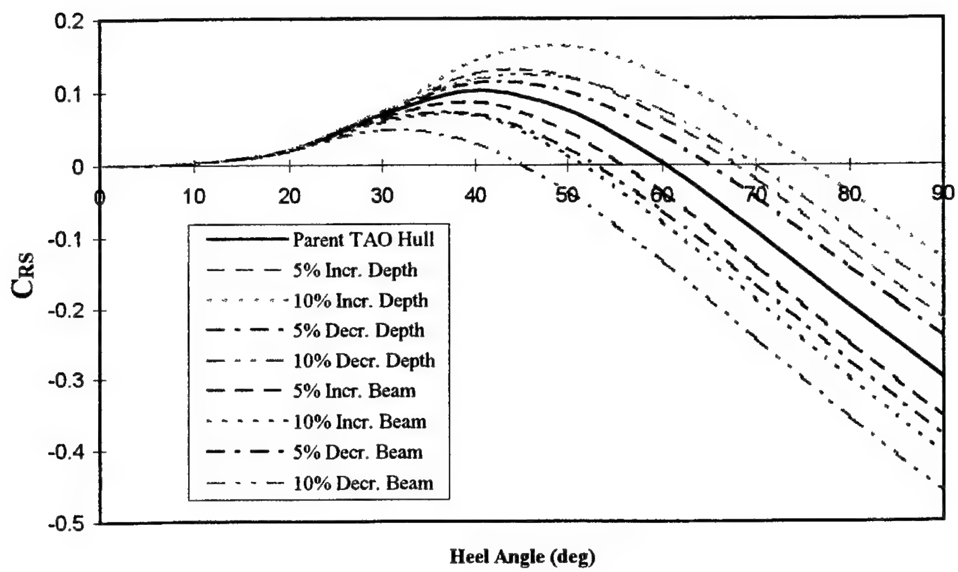

Figure 22. Comparison of Beam and Depth Effects on CRS for T-AO

that a ten percent increase in beam had the same effect on MS as did a ten percent decrease in depth. Oddly enough, due to the differences in BM_T, this pattern was not evident in the C_{RS} plots, shown in Figure 22.

Another trial was conducted in the same manner of varying beam and depth, except this time the draft was held constant at 17 feet for the FFG-7 and 30 feet for the T-AO. These drafts correspond to a displacement which is 41 percent of the total displacement of the hull ($\nabla/\nabla_T = 0.41$), chosen merely to maintain consistency between the two hull forms. The results obtained were nearly identical to the data from the constant displacement tests, indicating that it is of no consequence which of these parameters are held constant. For uniformity, it was decided that all further tests would maintain constant displacement, unless the objectives of the test made that impractical.

Successive trials were then performed for each of the parameters B/T, B/F, T/D and B/D. The control parameter was held constant for all the variants of that test, while the others were allowed to vary. The GZ, MS and C_{RS} curves of all the variants were compared to assess whether there were any common features between the variants that may be associated with the control parameter. The curves were also examined to determine if there was any correlation between them that may be associated with the varied parameters.

For the series of ships with constant B/T, it was noted that the righting arm curves, are fairly similar despite changes in depth and beam of as much as ten percent. The MS and C_{RS} curves on the other hand, depict vastly differing curves. Figures 23 and 24 show the GZ curves and the C_{RS} curves for this test respectively. The C_{RS} curve for the ship with the increased beam and draft has no positive region at all, while the curve for the ship with decreased beam and draft shows positive C_{RS} out to nearly 50 degrees of inclination. It appears that the increase in GM, owing to the larger beam and displacement, is offset by the loss of C_{RS}, resulting in comparable righting arms. This loss of C_{RS} may be attributed to the decrease in freeboard.

These results, as well as the grouping of the curves discussed previously, led to speculation that the deck edge immersion angle ϕ_D, and hence the B/F ratio, had a significant influence on the residuary stability. Table III contains a list of the eight variants

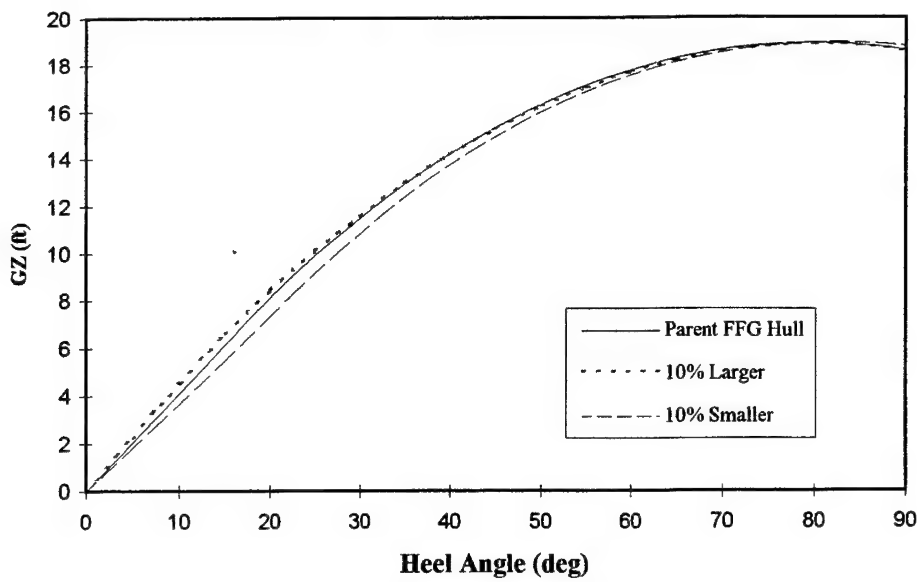

Figure 23. Righting Arm Curves for Ships of Constant B/T

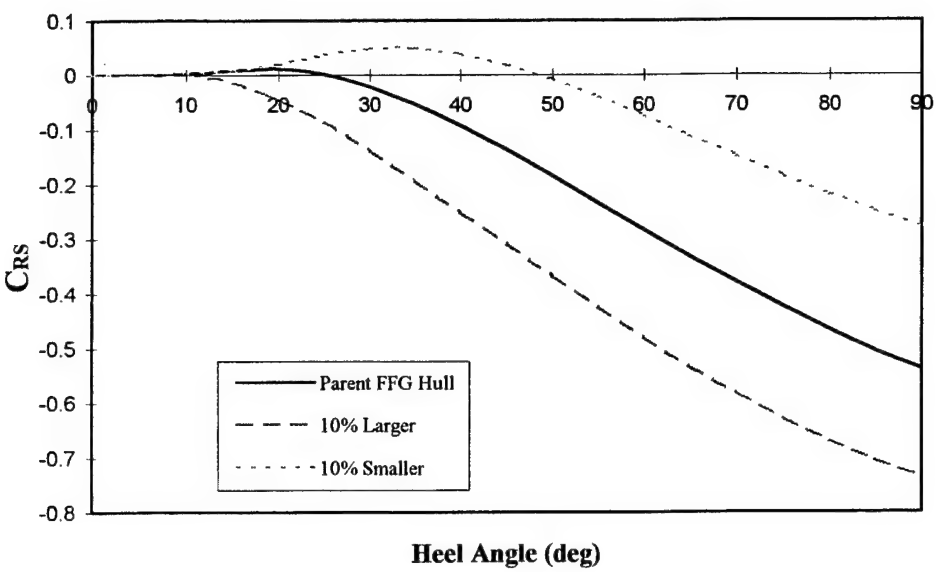

Figure 24. Residuary Stablitity Coefficient for Ships of Constant B/T

from the previous test, along with their corresponding ϕ_D and ϕ_B. Tests comparing models of constant B/F however, showed no specific trends in the MS or C_{RS} data. To validate the results, the tests were performed on the FFG-7 at two separate displacements (corresponding to ∇/∇_T of 1/2 and 2/3) with similar results. This indicated that perhaps the residuary stability is influenced by a combination of ϕ_D and ϕ_B, as is the case in Equations (17) and (18).

Variant	ϕ_D
10% Increased Beam	35.3
10% Decreased Depth	29.6
5% Increased Beam	37.5
5% Decreased Depth	44.4
10% Decreased Beam	36.0
10% Increased Depth	33.0
5% Decreased Beam	37.1
5% Increased Beam	40.3

Table III. Deck Edge Immersion Angle for Eight Variants

The results of the T/D analysis depart somewhat from the findings of Prohaska, when he concluded that the maximum C_{RS} value occurred when the draft was equal to one-half of the depth of hull. For the full formed tanker hull, which are very similar to the hull studied by Prohaska, the maximum C_{RS} is indeed nearly half of the depth. As can be seen in Figure 25, when maximum C_{RS} is plotted versus T/D for these vessels, the peaks of the curves fall at T/D ratios between 0.53 to 0.55. Where finer formed hulls are considered, the maximum C_{RS} occurred at a much higher T/D of approximately 0.63, as shown in Figure 26. This difference equates to roughly four to five feet of additional draft for the typical frigate hull. This jump in the T/D producing the maximum C_{RS} is undoubtedly due to the bilge fineness, or high deadrise, of this type of vessel.

The models with constant B/D produced results with the expected behavior. As anticipated, the ship with the largest beam and depth produced the highest MS and C_{RS} curves, and vice versa. Since the comparison was made with displacement held constant for all models, the ship with the largest beam had the least draft. This lower draft, coupled with it's large depth, gave this model significantly more above-water hull. Therefore,

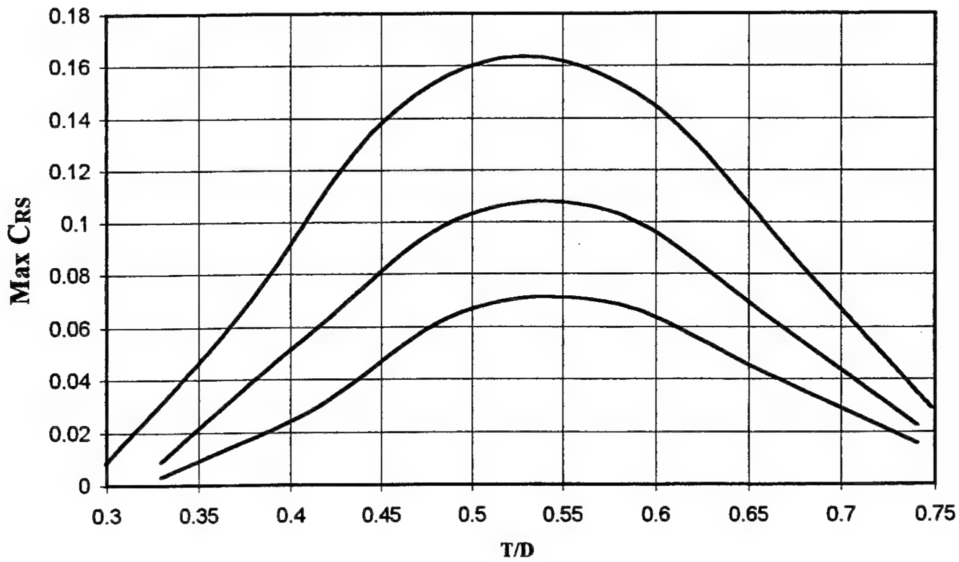

Figure 25. Maximum Residuary Stability vs. T/D for T-AO

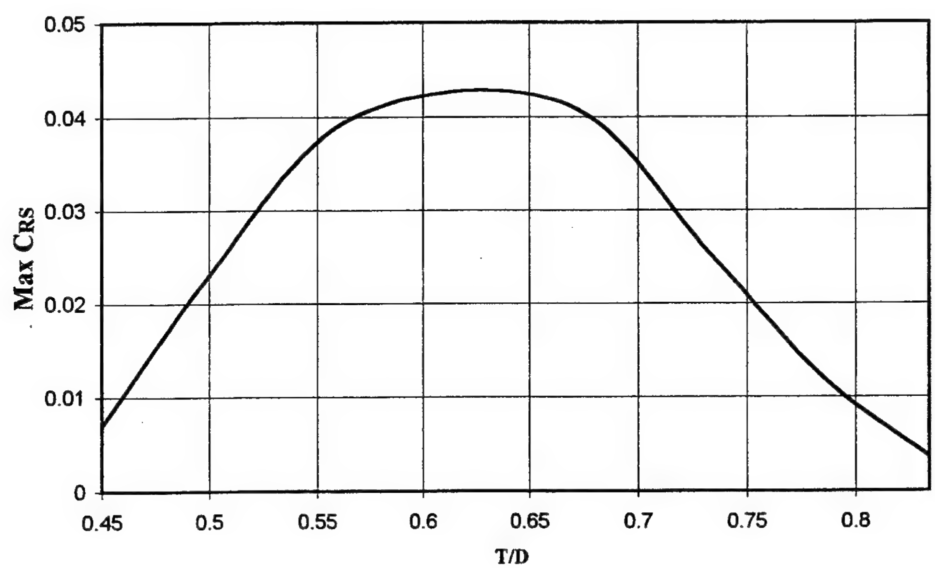

Figure 26. Maximum Residuary Stability vs. T/D for FFG-7

constant B/D is not exactly a fair comparison, unless B/T (and B/F by default) is also kept constant. This produces a series of models which are, in the transverse plane, geometrically similar. That is to say, since all of the control parameters, plus the form coefficients C_B and C_P, are kept constant, the cross-section of each ship is like a scaled model of the others. It should be noted however, that since length is of no significance and is not varied, these are not geometrically similar in the purest sense.

This transverse "geo-sim" analysis provided the most interesting phenomenon of this phase of research. All of the variants of each hull form produced a C_{RS} curve that was identical to that of the parent hull, as seen in Figures 27 and 28. The explanation to this likely lies in the geometry of the test. It can be shown that

$$BM_T \propto \frac{B^2}{T} \tag{19}$$

so that a ten percent increase in beam and draft will result in a ten percent increase in BM_T. It was also noted that GM increased by ten percent when this was done, with the center of gravity fixed. It would also stand to reason, that if beam and draft were increased by ten percent, with form coefficients held constant, that the submerged volumes and resultant righting arms would likewise increase by ten percent. From Equations (10) and (11), it can be seen that these factors could combined to necessitate the C_{RS} remaining constant.

Although the MS curves were not identical, since each variant had a slightly different BM_T, the curves all crossed the horizontal axis at the same angle. So, although each ship produced different righting arms, they all attained the maximum righting arm at the same angle, as would be expected.

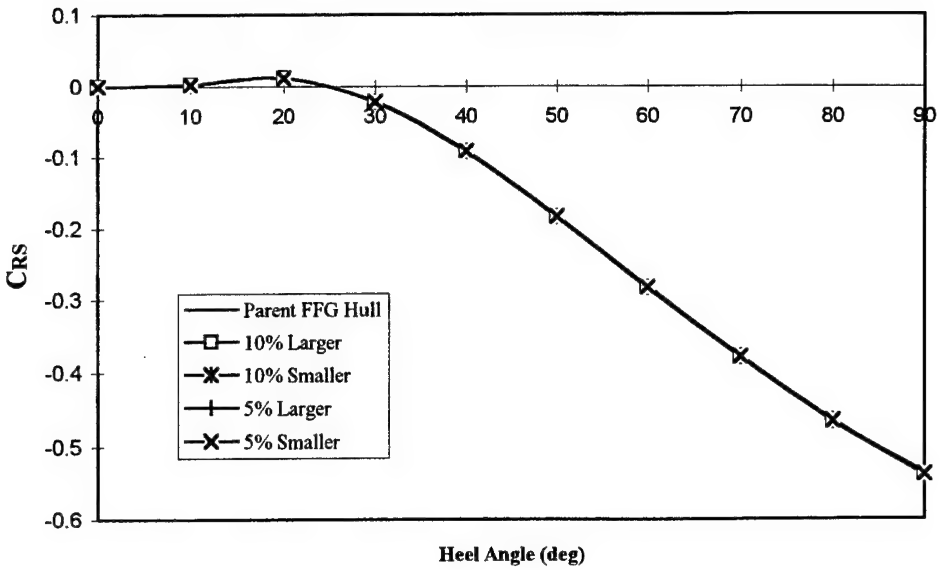

Figure 27. Residuary Stability Coefficient for "Geo-Sim" FFG-7

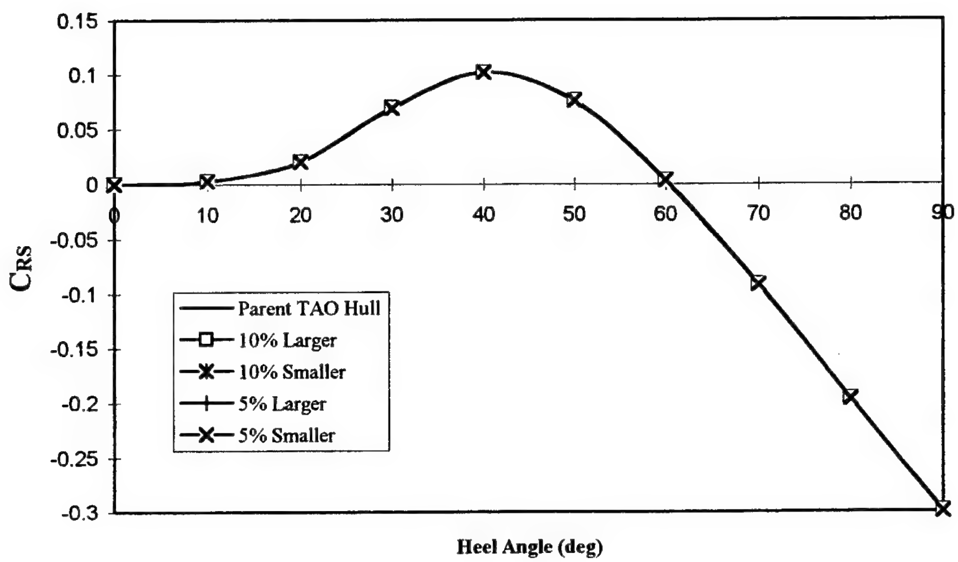

Figure 28. Residuary Stability Coefficient for "Geo-Sim" T-AO

B. BEHAVIOR OF THE RESIDUARY ENERGY COEFFICIENT

Although these trials provided some interesting qualitative results, no direct relationship between C_{RS} and the control parameters was found. An alternate approach was then developed with the dynamic stability criteria in mind. As explained earlier, Brown (1979) approximated the value of C_{RS} at thirty degrees of heel using parametrics. In and of itself though, the value of C_{RS} at thirty degrees does nothing to explain the righting characteristics of the ship through a range of heel angles. By integrating the C_{RS} curve up to a particular angle, as proposed by Khoushy (1979), one can readily see the contribution that the hull form has on the righting energy at that angle. A value of forty-five degrees was chosen for the upper limit of this integration for three reasons:

(1) it represents a typical range of heel angle for most monohull ships
(2) it is approximately the angle at which downflooding and deckhouse influence will occur causing irregular behavior of the righting arm curve
(3) the current U.S. Navy Damage Stability Criteria employ the use of forty-five degrees as the upper limit for determining the righting energy (Bartholomew, Marsh and Hooper, 1992).

The final stage of research was therefore aimed at analyzing the relationships between the control parameters and the integral of C_{RS} from zero to forty-five degrees. This integral has been called, for the purposes of this research, the *Residuary Energy Coefficient* and is hereafter referred to as $\overline{C_{RS}}45$. Numerical integration of the C_{RS} data was performed using the Composite Simpson's Method, which combines Simpson's Rule with the Trapezoidal Method. This method produces a more accurate result of continuous curves than either of the individual methods.

Six representative hull models were chosen for evaluation, three from the FFG-7 group and three from the T-AO group. As shown in Table IV, each hull represents a constant B/D model, which in turn was evaluated at a series of seven drafts, further defining the T/D, B/F and B/T ratios. $\overline{C_{RS}}45$ was then plotted against the control variables, as seen in Figures 29 through 32.

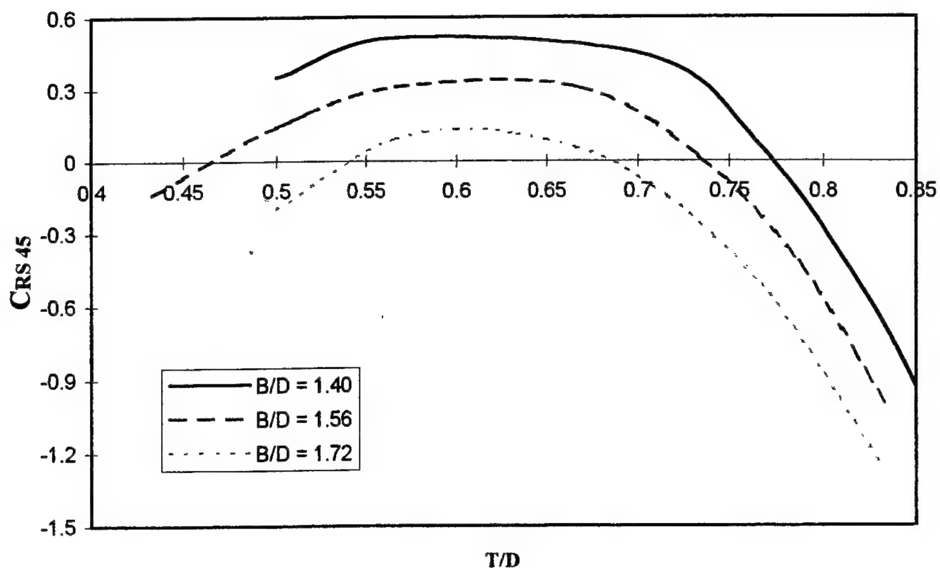

Figure 29. Residuary Energy Coefficient vs. T/D for FFG-7

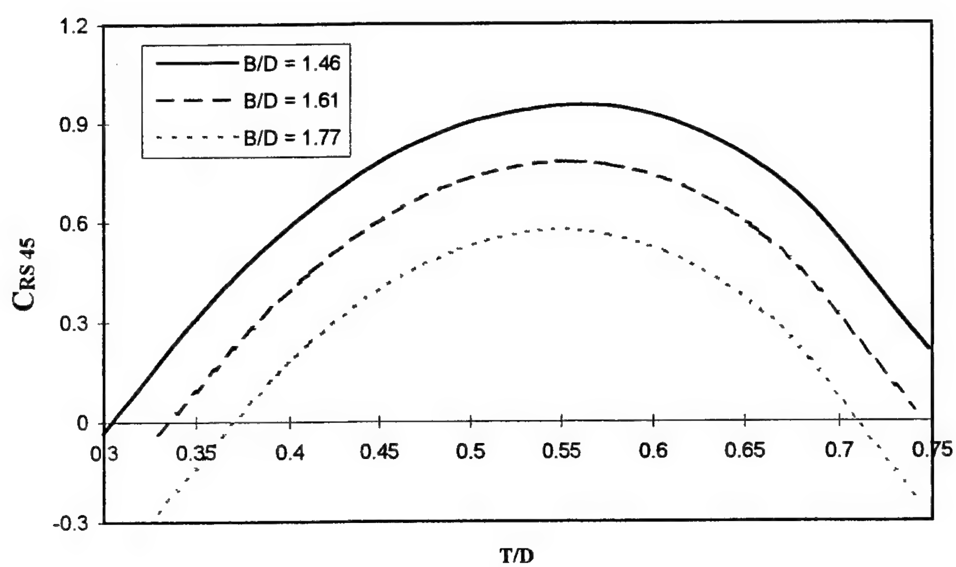

Figure 30. Residuary Energy Coefficient vs. T/D for T-AO

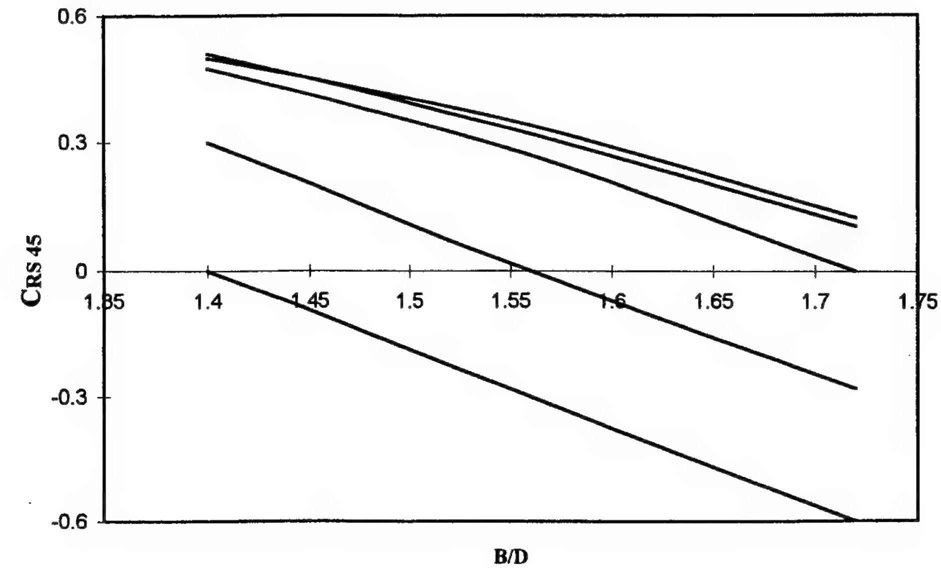

Figure 31. Residuary Energy Coefficient vs. B/D for FFG-7

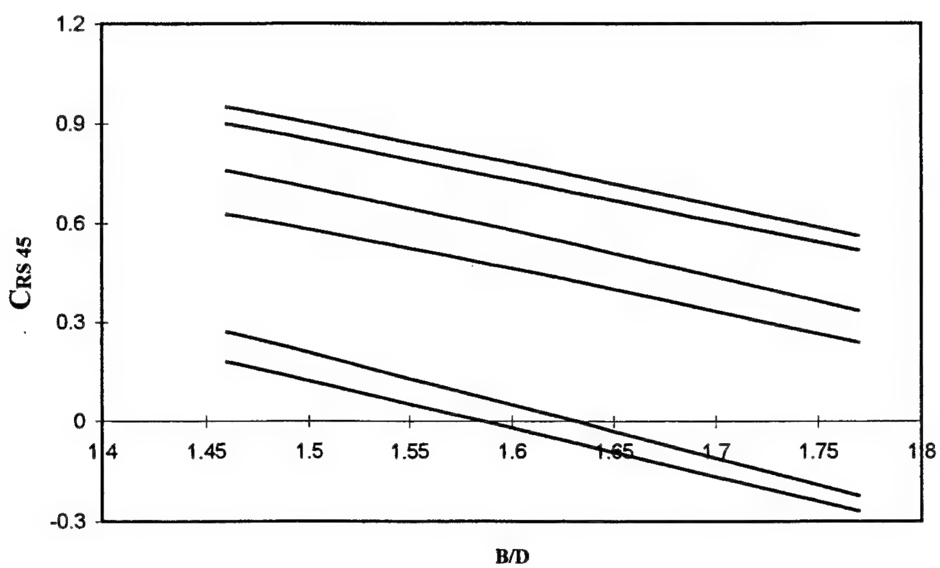

Figure 32. Residuary Energy Coefficient vs. B/D for T-AO

Model	B/D
Frigate A	1.40
Frigate B	1.56
Frigate C	1.72
Tanker A	1.46
Tanker B	1.61
Tanker C	1.77

Table IV. B/D Ratios of Selected Models

Figures 29 and 30 show $\overline{C_{RS}}45$ plotted against T/D, each curve representing a line of constant B/D. It is clear that the data of $\overline{C_{RS}}45$ produced smooth curves, throughout the range of T/D considered, that appeared evenly spaced for equal changes in the B/D ratio. When the same data was plotted as $\overline{C_{RS}}45$ versus B/D, as seen in Figures 31 and 32, the results were a series of lines of constant T/D which were very nearly linear. This relationship appears to have confirmed the earlier suspicion that C_{RS} is in some way influenced by a combination of both the deck edge immersion angle and the bilge pocket emergence angle.

C. DETERMINATION OF PARAMETRIC RELATIONSHIPS

Based on the behavior of $\overline{C_{RS}}45$ outlined above, it was concluded that the number of control parameters used to establish a parametric relationship could be reduced to two. It had become apparent that the $\overline{C_{RS}}45$, at least for a single type of vessel, could be expressed in terms of B/D and T/D, or stated simply

$$\overline{C_{RS}}45 = f\left(\frac{B}{D}, \frac{T}{D}\right) \tag{20}$$

A linear approximation method was used to test the linearity of the relationship with B/D describe above. Comparison of the approximation line with the actual data, shown in Figure 33, verifies that indeed $\overline{C_{RS}}45$ is a linear function of B/D. Furthermore,

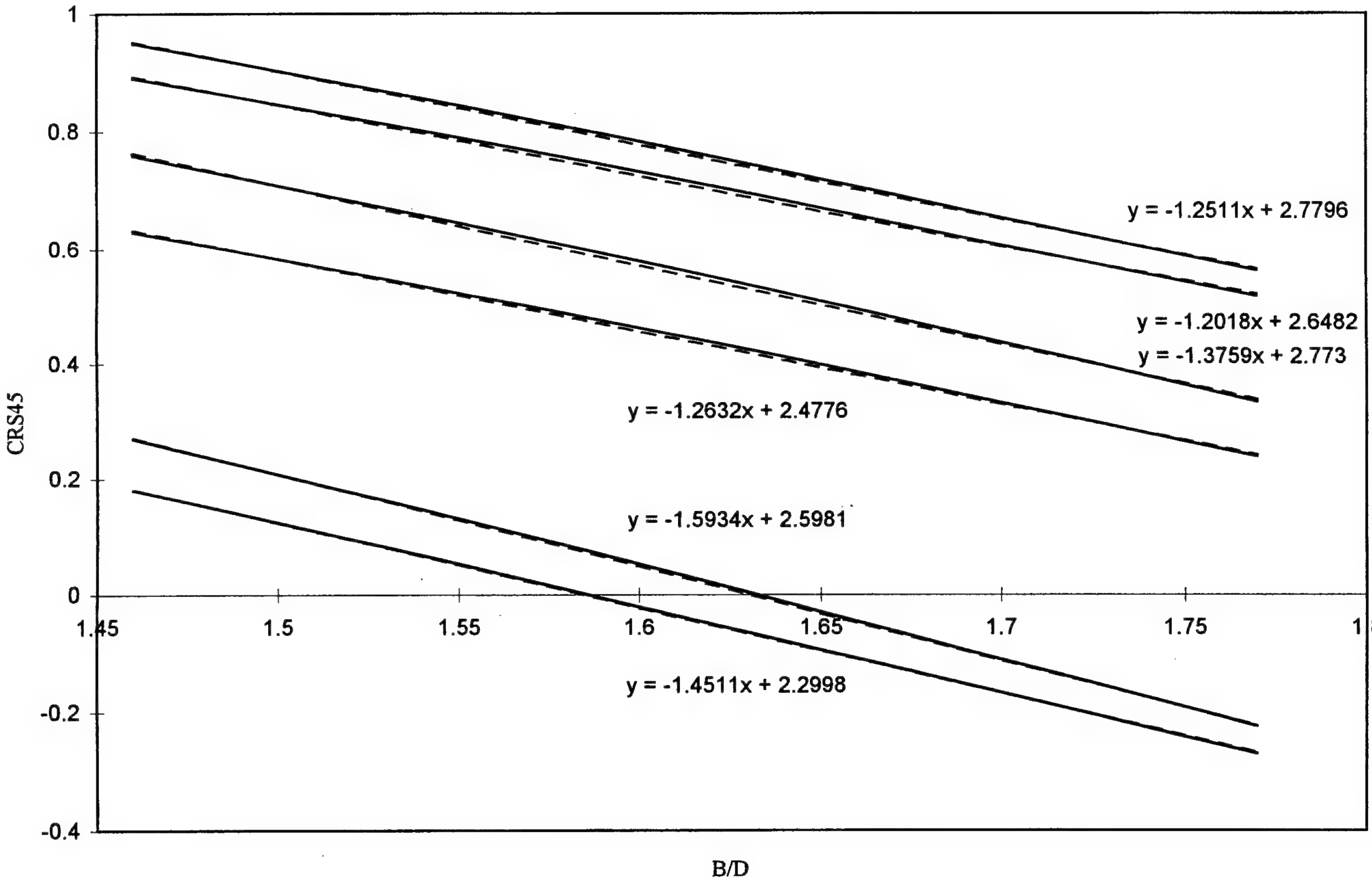

Figure 33. Actual Data vs. Linear Approximation (dashed)

the curves of $\overline{C_{RS}}45$ versus T/D, were all tested using several polynomial approximation methods. It was discovered that each of the curves could be fit reasonably well with a cubic approximation. The comparison between these approximated curves and the actual data, shown in Figure 34 and 35, demonstrates only minor deviations.

With $\overline{C_{RS}}45$ known to be a linear function of B/D and a cubic function of T/D, a regression analysis technique was then used on the data to formulate an equation. The following is the resultant parametric prediction for the residuary energy coefficient:

$$\overline{C_{RS}}45 = \alpha_1 \left(\frac{T}{D}\right)^3 + \alpha_2 \left(\frac{T}{D}\right)^2 + \alpha_3 \frac{T}{D} + \beta \frac{B}{D} + \lambda \qquad (21)$$

where the coefficients of α_1, α_2, α_3, β and λ are defined for a frigate type hull and a tanker hull as listed in Table V. Tables VI and VII show the regression analysis data for the FFG-7 and T-AO data respectively.

	Frigate	Tanker
α_1	-33.63	10.90
α_2	40.96	-0.71
α_3	-12.145	10.75
β	-1.66	-1.38
λ	2.75	-0.88

Table V. Coefficients for Frigate and Tanker Hulls

D. ACCURACY OF THE PARAMETRIC EQUATION

To test the accuracy of this equation, a numerical experiment was conducted on a tanker hull that was not used in the development of the equation itself. The hull model selected had a length of 650 feet, a beam of 105 feet, and a depth of 62.57 feet. This test model was given a displacement of 46,762 long tons, resulting in a draft of 27 feet, and was assigned an arbitrary center of gravity. The righting arms, residuary stability and C_{RS} were all calculated as before using GHS. The residuary stability and C_{RS} were numerically integrated to 45 degrees, once again using the Composite Simpson's Rule. Equation (21)

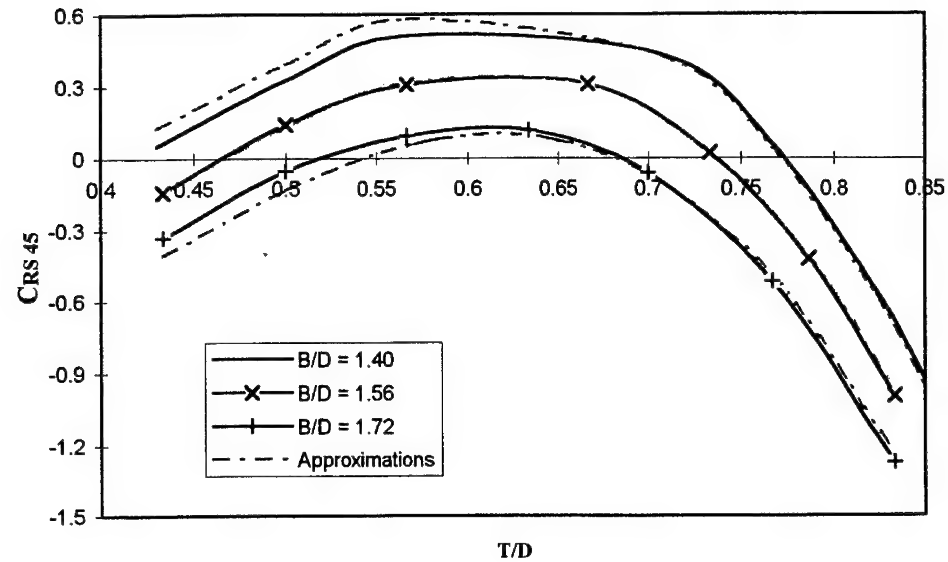

Figure 34. Residuary Energy Coefficient Approximations for FFG-7

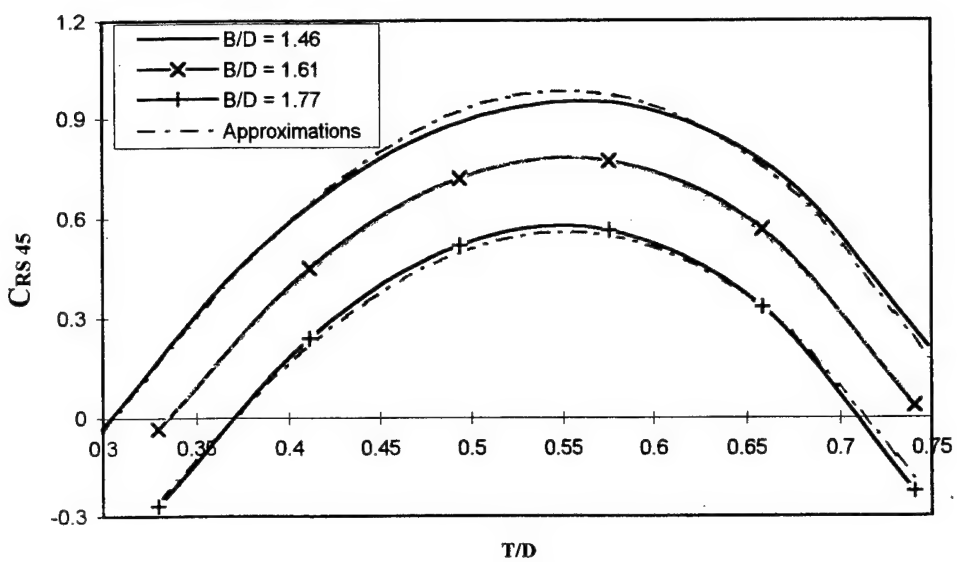

Figure 35. Residuary Energy Coefficient Approximations for T-AO

Regression Statistics	
Multiple R	0.998779382
R Square	0.997560255
Adjusted R Square	0.996747006
Standard Error	0.030038108
Observations	17

ANOVA

	df	SS	MS	F	Significance F
Regression	4	4.427117182	1.106779295	1226.636459	1.47318E-15
Residual	12	0.010827455	0.000902288		
Total	16	4.437944637			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 99.9%	Upper 99.9%
Intercept	2.753925343	1.122030054	2.454413172	0.030347179	0.309231909	5.198618777	-2.090825714	7.5986764
B/D	-1.658140646	0.06091998	-27.2183386	3.72545E-12	-1.790873877	-1.525407414	-1.921183633	-1.395097658
T/D	-12.14523951	5.377994892	-2.25832113	0.043341965	-23.86288358	-0.427595441	-35.36658403	11.07610501
T/D^2	40.95625261	8.453551998	4.844857241	0.000401729	22.53754537	59.37495984	4.455131414	77.4573738
T/D^3	-33.63322291	4.343368909	-7.74357961	5.23995E-06	-43.09661065	-24.16983517	-52.38721354	-14.87923228

Table VI. Regression Analysis Data for FFG-7

Regression Statistics	
Multiple R	0.998631414
R Square	0.997264701
Adjusted R Square	0.996483186
Standard Error	0.022187002
Observations	19

ANOVA

	df	SS	MS	F	Significance F
Regression	4	2.512643459	0.628160865	1276.06741	9.14289E-18
Residual	14	0.006891683	0.000492263		
Total	18	2.519535142			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 99.9%	Upper 99.9%
Intercept	-0.881066833	0.326710046	-2.696785251	0.01736562	-1.581790813	-0.180342852	-2.233748003	0.471614338
B/D	-1.383163127	0.040407586	-34.23028389	6.7363E-15	-1.469828856	-1.296497398	-1.550463095	-1.215863159
T/D	10.74944807	1.990766279	5.39965348	9.367E-05	6.479675255	15.01922088	2.507056701	18.99183943
T/D^2	-0.707214279	3.894029402	-0.181615033	0.8584881	-9.059084131	7.644655573	-16.82970674	15.41527818
T/D^3	-10.89935755	2.445002667	-4.457810086	0.00054123	-16.14337138	-5.655343712	-21.02242879	-0.776286305

Table VII. Regression Analysis Data for T-AO

was also used to obtain the integration of C_{RS}, which when multiplied by the BM_T, produced the integration of MS. The numerically obtained results were then compared to these predicted results. As shown in Table VIII, the parametric equation predicted the area under the residuary stability curve within a 1.6 percent error. Though additional testing must yet be done to determine the precision of this prediction equation, these results show that the relationship has some validity.

	GZ	**MS**	**C_{RS}**
0	0	0	0
5	3.899	0.010288	0.000417
10	7.812	0.064172	0.002602
15	11.758	0.210021	0.008517
20	15.759	0.498758	0.020225
25	19.844	0.987633	0.040050
30	23.9	1.591017	0.064518
35	27.536	1.944185	0.078840
40	30.648	1.968123	0.079810
45	33.148	1.598331	0.064815
	Method	**Integral MS**	**C_{RS}45**
	Numerical	16.1467	0.65477
	Parametric	15.8939	0.64452
	Percent Error	1.566	1.566

Table VIII. Comparison of Numerical and Parametric Methods

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this research convincingly show that predictions of the residuary stability of a ship are quite possible. Although only two hull forms were used in the development of the general equation, it is expected that the equation applies to all monohull ships. The values for the coefficients α_1, α_2, α_3, β and λ could easily be developed for destroyers, ice breakers and fishing vessels alike, in the same manner as presented here.

The potential uses for this equation however, have far more outreaching effects than the mere prediction of the residuary energy coefficient. Residuary stability alone is of very little practical use for the naval architect. However, coupled with either the knowledge of the precise loading conditions or some proven approximate methods, this equation can be directly related to the overall transverse stability of a ship. This could prove to be a very useful tool in today's maritime industry.

The greatest advantage of this method of stability assessment is that it can closely approximate the righting energy without a large amount of information about the ship. It could therefore be useful to the naval architect in defining and refining the hull form to optimize the preliminary design. This method could also benefit the salvage engineer, who may need to assess the damaged stability of a vessel with very limited information and computing power available. The primary applications for this type of stability assessment can therefore be grouped into two categories: its application to preliminary design and its application for rapid stability assessment.

A. APPLICATION TO PRELIMINARY DESIGN

In a traditional design spiral, the choice of hull geometry for the initial iteration is based on a preliminary estimate of payload volume or overall volume. At this early stage, these volumes often have to be scaled from historical data. The evaluation of transverse stability, typically occurs many steps later, after the machinery selection and location is completed. If the stability is found to be inadequate, the designer must currently use qualitative methods to improve it, such as increasing beam or lowering machinery

location, which is not always feasible. This results in somewhat of a trial and error approach to designing ships. Though much more time efficient, even the latest ship synthesis programs, perform stability checks near the end of each iteration of the design spiral.

The techniques of numerical integration used in evaluating the transverse stability of a ship are reliable and reasonably accurate, at least within the margin of error of today's construction standards. The residuary energy method is not intended to replace these techniques. The drawback to these techniques, however, is that a complete body plan is needed, during each iteration, to conduct such an assessment. This residuary energy method may be used to establish an optimal ship geometry, not just for the initial starting point, but for each subsequent iteration as well. This would allow the design to converge on a solution with fewer iterations and less processing time.

In order to use this method in such a way, the entire righting energy equation must be "parameterized". The righting energy at 45 degrees can be expressed almost entirely in terms of the principal characteristics of a ship, through a series of substitutions. First, combining Equations (9) and (10), it can be seen that

$$\textit{Righting Energy}\,(\phi = 45) = \int_0^{45} \left(\Delta GM \sin\phi + \Delta BM_T C_{RS}\right) d\phi \tag{22}$$

Since displacement remains constant during the heeling process and the terms GM and BM_T both refer to the initial or upright condition, this can be expressed as

$$\textit{Righting Energy}\,(\phi = 45) = \Delta\, GM\int_0^{45} \sin\phi\, d\phi + \Delta\, BM_T \int_0^{45} C_{RS}\, d\phi \tag{23}$$

Performing the integration and using the definition of the residuary energy coefficient, this reduces to

$$\textit{Righting Energy}\,(\phi = 45) = 0.293\,\Delta\, GM + \Delta\, BM_T\, \overline{C_{RS}}\, 45 \tag{24}$$

Substituting Equation (1) for GM, we can express this as

$$Righting\ Energy\,(\phi = 45) = 0.293\,\Delta\,(KB - KG) + \Delta\,BM_T\,\left(\overline{C_{RS}}45 + 0.293\right) \qquad (25)$$

Using the approximation from Equation (8), and knowing that $\nabla \approx 35\,\Delta$ for seawater, a new expression for $\Delta\,BM_T$ can be obtained. Furthermore, the Morrish Formula from Equation (6), can be modified using the definition of the vertical prismatic coefficient (C_{VP}), to express KB as shown.

$$\Delta\,BM_T = \frac{LB^3}{420}\left(1.204C_P - 0.157\right) \qquad (26)$$

$$KB = \frac{T}{3}\left(2.5 - C_{VP}\right) \qquad (27)$$

Combining these three equations, the righting energy at 45 degrees can be estimated by

$$R.E._{@45} = 0.098\Delta T\left(2.5 - C_{VP}\right) - 0.293\Delta KG + \frac{LB^3}{420}\left(1.204C_P - 0.157\right)\left[\overline{C_{RS}}45 + 0.293\right]$$

where $\overline{C_{RS}}45$ can be expressed in terms of T, D and B using Equation (21). This approximation is now a function of basic hull form parameters (B, L, D, T, C_P, C_{VP}) and KG, which is defined by location of machinery and other major weights. Initially KG can also be reliably approximated as a function of depth, however, actual weight calculations performed during each iteration of the design will prove more accurate (Bartholomew, Marsh and Hooper, 1992). With this relationship, optimization techniques can be used to define the hull form which maximizes the righting energy, subject to certain constraints. Appendix B shows an example of a design optimization, which optimized the hull characteristics of the FFG-7 frigate with this expression, using the Fortran-based Automated Design Synthesis (ADS) program.

Another finding that may aid in the preliminary design is that for each of the vessels studied, there was a distinct T/D ratio that produced the maximum C_{RS}. This is to say that, for a given hull depth and beam, there is a draft that will produce the maximum value of C_{RS} for that hull. This occurred at a T/D of approximately 0.63 for the FFG-7 and 0.53 to 0.55 for the T-AO. Care must be taken when using this though, because BM_T decreases as draft increases for a given hull. As a result, the T/D corresponding to maximum C_{RS} may not necessarily correspond to the maximum MS.

B. APPLICATION FOR RAPID STABILITY ASSESSMENT

When there is little known about a ship, as may be the case in some salvage operations, this method could be used to quickly assess the righting energy at 45 degrees. More importantly, this technique of stability assessment could be integrated into a salvage software application, such as the U. S. Navy's Program of Ship Salvage Engineering (POSSE). In doing this, stability analyses could be performed for a variety of damage scenarios, as well as various salvage efforts, allowing for improved strategic planning.

This assessment is an easier and more direct way to accomplish what was done for the preliminary design application. In this case where a ship already exists, GM is usually estimated very reliably using the period of roll of the ship's motion (Bartholomew, Marsh and Hooper, 1992). This allows the use of Equation (24) directly, leaving only BM_T to be approximated in the same manner as above. Because the $\overline{C_{RS}}45$ can be determined parametrically, the user needs only L, B, D, T, Δ and C_P, in addition to the already estimated GM, to determine the righting energy. Since these hull parameters are the most basic and readily accessible characteristics of a ship, this should prove to be a very easy method to determine the righting energy through 45 degrees of heel.

C. RECOMMENDATIONS

It is hoped that this research will prove to be merely the first step in a series of studies into the parametric prediction of dynamic stability. The following recommendations, suggesting potential avenues for future studies, shows that there is much more exploration to be done in this area.

Further research is necessary to develop the prediction coefficients for other existing hull forms. While the general equation can likely be used for any hull form, the coefficients for each term in the equation vary widely between different hull forms. The coefficients determined in this research provide good results for the frigate and tanker hull forms, but neither set of coefficients could be used to predict the transverse stability for a trawler, for instance. Not until a complete database of existing hull forms is established that perhaps a relationship may be found which relates to a wide range of hull forms. It is conceivable however, that no such relationship exists and that the user will have to select the proper coefficients based on the nearest base ship to the hull form of concern.

Future studies should also consider additional parameters. While the parameters of T/D and B/D were used in the final results of this research, a different group of control parameters may prove to more closely approximate the transverse stability for all ships using just one set of coefficients. Although the parameters of B/F and B/T were not used in the end result, it is quite possible that when combined with another parameter, they may prove to be more effective. Among the geometric parameters not considered during the course of this investigation, the dimensions of hull flare and tumblehome probably have the most influence on stability, as was seen in Figure 3. It is therefore suggested that a non-dimensional version of these parameters, perhaps normalized by freeboard, be included in future research.

Ultimately, the research in this field should culminate in an improved dynamic stability criterion. While it is desired to develop a standard that more accurately reflects the nonlinear dynamics of ship motion, this method is probably better suited to be used for adapting today's standards to a more easily used method. A statistical analysis should be undertaken to determine the minimum level of $\overline{C_{RS}}45$ required to satisfy certain dynamic stability criteria. The resulting standard would be as easy to apply as the minimum GM standard. In fact, it would most likely work in conjunction with this standard to set criteria for the minimum GM and $\overline{C_{RS}}45$ combination.

APPENDIX A. HULL GEOMETRY FOR FFG-7 AND T-AO 187 VARIANTS

Hull	Beam	Depth	Draft
Parent FFG	44.8	30	Various
10% Increase Beam	49.3	30	Various
10% Decrease Beam	40.3	30	Various
5% Increase Beam	47	30	Various
5% Decrease Beam	42.6	30	Various
10% Increase Depth	44.8	33	Various
10% Decrease Depth	44.8	27	Various
5% Increase Depth	44.8	31.5	Various
5% Decrease Depth	44.8	28.5	Various
Constant B/F			
Parent FFG	44.8	30	19.4
10% Increase Beam	49.3	29.7	18.7
10% Decrease Beam	40.3	33.3	22.8
Constant B/T			
Parent FFG	44.8	30	23.6
10% Increase Beam	49.3	30	26
10% Decrease Beam	40.3	30	21.2
Constant B/D			
Parent FFG	44.8	30	23.6
10% Increase Beam	49.3	33	22.8
10% Decrease Beam	40.3	27	24.6
"Geo-Sim"			
Parent FFG	44.8	30	23.6
10% Larger	49.3	33	26
10% Smaller	40.3	27	21.2

Hull	Beam	Depth	Draft
Parent TAO	97.6	60.8	Various
10% Increase Beam	107.4	60.8	Various
10% Decrease Beam	87.8	60.8	Various
5% Increase Beam	102.5	60.8	Various
5% Decrease Beam	92.7	60.8	Various
10% Increase Depth	97.6	66.8	Various
10% Decrease Depth	97.6	54.7	Various
5% Increase Depth	97.6	63.8	Various
5% Decrease Depth	97.6	57.7	Various
Constant B/T			
Parent TAO	97.6	60.8	35.5
10% Increase Beam	107.4	60.8	39.1
10% Decrease Beam	87.8	60.8	32
Constant B/D			
Parent TAO	97.6	60.8	35.5
10% Increase Beam	107.4	66.8	33.3
10% Decrease Beam	87.8	54.7	38.1
"Geo-Sim"			
Parent TAO	97.6	60.8	35.5
10% Larger	107.4	66.8	39.1
10% Smaller	87.8	54.7	32

APPENDIX B. DESIGN OPTIMIZATION USING RESIDUARY ENERGY

The following is a simplified example of an optimization performed for the preliminary design of a ship. The objective is to find the optimum principal hull characteristics of a preliminary design by maximizing the righting energy that the ship will possess at an angle of heel of 45 degrees. The numerical optimizer used is the FORTRAN-based Automated Design Synthesis (ADS) program, which contains a wide variety of algorithms to optimize either constrained or unconstrained problems using both linear and non-linear programming (Vanderplaats, 1985).

Chapter V shows the development of the parametric equation for the righting energy using some reliable approximation methods. It was shown that, for a heel angle of 45 degrees the righting energy can be expressed as:

$$R.E._{@45} = 0.098\Delta T\left(2.5 - C_{VP}\right) - 0.293\Delta KG + \frac{LB^3}{420}\left(1.204C_P - 0.157\right)\left[\overline{C_{RS}}45 + 0.293\right]$$

where $$\overline{C_{RS}}45 = \alpha_1\left(\frac{T}{D}\right)^3 + \alpha_2\left(\frac{T}{D}\right)^2 + \alpha_3\frac{T}{D} + \beta\frac{B}{D} + \lambda$$

For this example, a frigate type hull will be used, for which the following coefficients apply:

α_1 = -33.633	β = -1.658
α_2 = 40.956	λ = 2.754.
α_3 = -12.145	

The following parameters were also held fixed to reduce the number of design variables to a manageable level:

Prismatic Coefficient (C_P)	0.685
Vertical Prismatic Coefficient (C_{VP})	0.768

This allows for the righting energy, also termed the objective function F(x), to be expressed in terms of just five parameters.

$$F(x) = \frac{BLT^2}{275.4} - \frac{BLT}{204.9}KG + \frac{LB^3}{629.0}\left[\alpha_1\left(\frac{T}{D}\right)^3 + \alpha_2\left(\frac{T}{D}\right)^2 + \alpha_3\frac{T}{D} + \beta\frac{B}{D} + \lambda\right]$$

These five parameters, which are to be optimized, are known as the design variables. They are defined in the ADS program as:

X(1) = Length (L)

X(2) = Beam (B)

X(3) = Depth (D)

X(4) = Draft (T)

X(5) = Vertical Center of Gravity (KG)

The constraints of the design, listed below, are several well-known naval architectural limits. They were chosen with the knowledge that an optimization of righting energy would tend to create a larger ship, while attempting to force KG toward zero and GM to an exceedingly high value.

$$\frac{GM_T}{B} \geq 0.08 \qquad \Delta \leq 4000$$

$$\frac{B}{T} \geq 2.5 \qquad \frac{L}{B} \geq 7.0$$

$$KG \geq \frac{D}{3}$$

To use these constraints in ADS, they must be expressed in terms of the design variables and normalized. Hence, these equations are transformed into the following set of constraint or g(x) equations.

$$g_1(x) = 1 - 9.3\frac{T}{B} - 1.193\frac{B}{T} + \frac{KG}{B} \leq 0$$

$$g_2(x) = \frac{BLT}{240137.2} - 1 \leq 0$$

$$g_3(x) = 1 - \frac{B}{2.5T} \leq 0 \qquad g_4(x) = 1 - \frac{L}{7B} \leq 0$$

$$g_5(x) = 1 - \frac{3KG}{D} \leq 0$$

The optimization program enclosed was initially run for nine different methods or strategies. A method was considered unfeasible if the constraints were violated by greater than one percent, indicated by a value greater than 0.01 in the "Max Value of Constraints" column of the results. Five of these methods appeared to converge to a solution near the optimum. These produced resulting righting energies of approximately 36,000 ft-tons. The remaining strategies were run again, this time with the program written to use scaling. Of these four, two of them produced comparable results to the first five.

Overall, four of the methods produced nearly identical ship parameters, fairly similar to the FFG-7 design. They all had a length of 408 feet, a beam of 38 feet and a depth of 30 feet. The righting energy for this design, approximately 36,000 ft-tons, was far surpassed by three other designs. These methods, which produced righting energies of over 39,000 ft-tons, were:

3-3-1-0 Unconstrained minimization using Quadratic Extended Interior Penalty Function Method, with Variable Metric Method (BFGS) and Polynomial Interpolation w/ bounds.

Optimization Results

ISTRAT	IOPT	IONED	ISCAL	Righting Energy (Obj)	Length	Beam	Depth	Draft	KG	Max Value of Constraints	Active Constraints	Number of Evals
0	5	7	0	35069	407.4	38.3	30.2	15.3	10.1	-0.00485	g2, g3, g5	47
0	5	6	0	35336	407.4	38.3	30.3	15.3	10.14	0.000475	g2, g3, g5	66
0	4	7	0	33341	407.2	37.6	29.7	15.1	10.3	0.0039	g2, g3, g5	47
6	5	7	0	43213	309.5	44	37.3	17.6	10.15	0.1825	g1, g2, g3	60
8	5	7	0	36136	407.5	38.5	30.4	15.4	10.1	0.00794	g1, g2, g3	55
1	3	3	0	824540	700	90	60	38.4	10	9.072	g2, g3, g5	121
2	3	3	0	779130	700	86.1	60	35.6	10	7.926	g2, g3, g5	130
3	3	1	0	39004	328.3	42.9	33.7	17	11.5	-0.00435	g2, g3	463
5	3	3	0	824500	700	90	60	38.3	10	9.057	g2, g3, g5	120
6	5	7	1	43481	308.7	44.1	37.8	17.6	10	0.2072	g1, g2, g3	72
1	3	3	1	41035	308.7	44.1	35.3	17.6	11.75	0.000011	g2 thru g5	369
2	3	3	1	44953	496.8	48.3	60	10	20	0.9332	g2, g5	514
5	3	3	1	41049	308.7	44.1	35	17.6	11.7	0.00033	g2 thru g5	298

1-3-3-1 Unconstrained minimization using Exterior Penalty Function Method, with Variable Metric Method (BFGS) and Polynomial Interpolation w/ bounds; scaling used.

5-3-3-1 Augmented Lagrange Multiplier Method with Variable Metric Method (BFGS) and Polynomial Interpolation w/ bounds; scaling used.

The last two combinations are considered to be the best choices for this optimization. They both produce righting energies of approximately 41,040 ft-tons and have four of the five constraints active. Although both of them indicate a violation of the constraints, the extent is so minute (the largest violation equates to KG being merely 0.001 inches too high) that it is neglected. Therefore, for the pre-determined form coefficients and the constraints outlined above, the optimal hull design for a 4000 ton frigate is as shown below. This design shows significant improvement over the FFG-7 design.

	Optimal Design	FFG-7
Length (ft)	308.7	408
Beam (ft)	44.1	44.8
Depth (ft)	35.3	30
Draft (ft)	17.6	16.05
KG (ft)	11.75	10
Righting Energy (ft-tons)	41,040	35,530

This particular design may not be the optimum for other steps along the design process, such as powering and machinery arrangements. The requirements of these processes, however, could be incorporated into this program as additional constraints.

```
c        THIS PROGRAM OPTIMIZES THE HULL CHARACTERISTICS BY PASSING
c        THE DESIGN VARIABLES, CONSTRAINTS AND OBJECTIVE FUNCTION TO ADS.

         REAL G1, G2, G3, G4, G5, OBJ
         DIMENSION X(6), VUB(6),VLB(6), G(5), IDG(5), IC(5), DF(6),
     &   A(6,5),WK(660), IWK(225)
         NRA=6
         NCOLA=5
         NRWK=660
         NRIWK=225
         IGRAD=0
         NDV=5
         NCON=5
         X(1)=408.0
         X(2)=44.8
         X(3)=30.0
         X(4)=16.055
         X(5)=10.0
         VLB(1)=100.0
         VLB(2)=35.0
         VLB(3)=15.0
         VLB(4)=10.0
         VLB(5)=10.0
         VUB(1)=700.0
         VUB(2)=90.0
         VUB(3)=60.0
         VUB(4)=40.0
         VUB(5)=35.0
         IDG(1)=0
         IDG(2)=0
         IDG(3)=0
         IDG(4)=0
         IDG(5)=0
         IPRINT=2030
         OPEN (UNIT=2, FILE='ship_out', STATUS='UNKNOWN')
         PRINT *, 'INPUT VALUES FOR ISTRAT,IOPT,IONED'
         READ(*,30) ISTRAT, IOPT, IONED
         INFO=-2
         CALL ADS (INFO,ISTRAT,IOPT,IONED,IPRINT,IGRAD,NDV,NCON,X,VLB,
     &   VUB,OBJ,G,IDG,NGT,IC,DF,A,NRA,NCOLA,WK,NRWK,IWK,NRIWK)
         IWK(2)=0
10       CALL ADS (INFO,ISTRAT,IOPT,IONED,IPRINT,IGRAD,NDV,NCON,X,VLB,
     &   VUB,OBJ,G,IDG,NGT,IC,DF,A,NRA,NCOLA,WK,NRWK,IWK,NRIWK)
         IF (INFO.EQ.0) GO TO 20
         T1=-33.633*(X(4)/X(3))**3+40.956*(X(4)/X(3))**2-12.145*X(4)/X(3)
     &   -1.658*X(2)/X(3)+3.047
         OBJ=-X(1)*X(2)*X(4)*(X(4)/275.4-X(5)/204.9)-X(1)*(X(2)**3)*T1/629
         G(1)=1-9.3*X(4)/X(2)-1.193*X(2)/X(4)+X(5)/X(2)
         G(2)=X(1)*X(2)*X(4)/240137.22-1
         G(3)=1-X(2)/(2.5*X(4))
         G(4)=1-X(1)/(7*X(2))
         G(5)=1-3*X(5)/X(3)
         GO TO 10
20       CONTINUE
         WRITE(2,40) OBJ,X(1),X(2),X(3),X(4),X(5)
         CLOSE (2)
         STOP
30       FORMAT (4I5)
40       FORMAT(//5X,7HOPTIMUM,5X,5HOBJ =,E12.5//5X,4HL =,E12.5,5X,
     &   4HB =,E12.5/5X,4HD =,E12.5,5X,4HT =,E12.5/5X,4HKG =,E12.5,5X)
         END
```

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